

INVESTIGATION OF WET PAPER COHESIVE PROPERTIES

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Splitting Weight = 125g

Splitting Weight = 233g

Splitting Weight = 330g

Splitting Weight = 550g

Splitting Weight = 770g

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LIST OF SYMBOLS AND ABBREVIATIONS

T_w	web tension [N/m]
W_w	work of separation [N/m]
\emptyset	angle of take off
m_w	mass of web per unit area [kg/m ²]
V_w	wire speed [m/s]
T	tensile strength [Nm/g]
Z	zero span tensile strength [Nm/g]
b	shear strength of the fiber to fiber bond [N/m ²]
P	fiber perimeter of the average fiber cross section [m]
L_f	fiber length [m]
C	fiber coarseness [g/m]
RBA	relative bonded area in the dry sheet
T_{ww}	tensile strength for wet webs [Nm/g]
RBA_{ww}	the proportion of the fiber surface that is contained within a water meniscus holding adjacent fibers together
γ	surface tension of water [dynes/cm] or [N/m]
μ	coefficient of friction between the two wet fibers
A	area within the water meniscus over which the surface tension forces act
r	radius of curvature of the water meniscus
F	force that pulls the fiber together
L	length of the line of contact between air, water and fiber
ΔP	compacting pressure gradient
X	thickness of the liquid film

-OH	hydroxyl groups
S ₂	fiber secondary wall
PAC	polyaluminum chloride
A/C PAM	anionic/cationic polyacrylamides
PCC	precipitated calcium carbonate
W'	Mardon total work done in the paper
ϵ	strain of the web
W _T	Osterberg total work done on the paper
W _S	work of separating the two surfaces
W _E	work of extension
W _M	work involved in increasing the web moment of inertia
C.S.F.	Canadian standard freeness
ADM	Archer Daniels Midland Company
CD	machine cross direction
MD	machine direction
h _i	initial height of the splitting weights
h _t	the height at a moment $t > 0$
m	total splitting weight
V _t	mean velocity of the splitting weights at time = t
NC	ash content obtained with normal clay
MC	ash content obtained with starch modified clay

SUMMARY

During production, the paper is transformed from a sheet high in water content to a sheet low in water content. At the same time as water is removed, the cohesive energy of the paper increases drastically. In this investigation the development of the sheet cohesive strength (bonding) is investigated through experimental testing, simulating the most important conditions the paper supports during its production.

The cohesive strength of the sheet of paper depends mainly on the entanglement of the individual fibers (friction resistance between fibers due to surface tension effects) when the consistency is low, and as the consistency goes up the cohesive strength of the sheet depends on the hydrogen bonding between the same fibers or bonding between the fibers and the chemical additives included in the sheet. Both the entanglement and the bonding can be manipulated during the production process through mechanical treatment (refinement, forming, pressing and drying) and/or chemical treatment.

In this thesis the cohesive strength of the paper was evaluated for consistencies that correspond with the paper production process, a range from 20% to 95% was considered. A number of additional variables were also investigated, these include basis weight, refining level, clay filler addition, and starch content. Cohesive strength was evaluated using a unique apparatus developed at IPST. Tensile strength and strain were also measured using a standard Instron device.

The results for all the tests performed show how the cohesive strength slowly increases in the range from 20 to 55% solids, and then it grows up exponentially following the same behavior of the stress-strain curve.

The primary results of this work were

1. A linear relationship between tensile index and cohesive energy index was established
2. The linear relationship between tensile index and cohesive energy has a basis weight dependence which is linear and can be eliminated yielding a single tensile index – cohesive energy index for a particular paper grade
3. The results from the splitting apparatus can be used to calculate strain based on the work of Osterberg. The resultant strain has an offset compared to that obtained from the Instron tensile test, but is consistent with Osterberg's results

CHAPTER 1

INTRODUCTION

The trend in today's paper industry is toward lower grammage papers, increased use of short fiber pulps, higher machine speeds and increased use of fillers as fiber substitutes. All these factors affect the properties of the paper, including reducing the strength properties of the final product. The wet web strength of the paper is also reduced, producing a web that can easily break during the normal production process, limiting the production capacity of the machine. To solve this problem, new paper machines have reduced or eliminated open draws in the sections of the machine where the sheet is at a low consistency. Some new machines have the first open draw after the web leaves the press section, when the sheet strength is high enough to support the tension required to peel the web from the press roll. The situation for old paper machines is quite different. They still have open draws between the wire and the first press, and among the different press sections, where the wet web is not yet consolidated and consequently the strength is still low. In many cases, the investment required to eliminate the open draws in this machines is so high that is not possible to accomplish such a change. This is one of the main reasons why the study of the wet web properties is of importance.

Paper properties are developed throughout the production process, starting at the wet end where different mechanical and chemical treatments are applied to the pulp suspension. This continues during the consolidation process, where the pulp suspension

is converted into a paper web that finally will develop the properties that the customer requires. Although the final properties of the sheet are of crucial importance, the evolution of properties through the process is a concern for the paper maker. Among these properties, the cohesive strength of the paper is one of the most important as it impacts peeling from press rolls fabrics and dryer cylinders.

There are two main sources for strength development as water is removed from the wet web: the first one, present at low consistencies, is due to internal surface tension forces and fiber entanglement, and the other one present at higher consistencies is due to the inter fiber bonding. There is not a single consistency where one source ends and the other starts, in reality there exists a region where both of them are present. At a high enough consistency the only source that remains is due to inter fiber bonding.

In this study the effects of the mechanical treatment (refining) and the chemical treatment were taken into consideration when analyzing the development of the wet web strength. For the case of mechanical treatment, three different levels of refining were evaluated. In the case of chemical treatment starch and filler additives were evaluated. Due to the importance of fillers as fiber substitutes, three different levels of ash (filler) content were evaluated. Additionally, the role of the cationic starch as paper strength additive was also evaluated. A primary objective was to quantify the cohesive strength loss due to the filler addition and also quantify how much of this loss could be recovered by cationic starch addition. Finally, the effect of the starch modified clay was also evaluated, to establish a comparison with the standard uncoated clay.

All the experiments were done using the same pulp (bleached softwood). The sheet formation was done using a Formette Dynamique. The same forming and pressing operation were used for all the samples produced. A steam heated drum dryer was used to dry the sample to the higher consistency levels. Since the forming and pressing operations were not changed the refining, starch addition, ash content, basis weight and solids content were the only variables.

Sheets were made using a Formette Dynamique and cut into strips which were then tested in the splitting apparatus. The splitting apparatus allows a determination of the cohesive strength of paper sheets at different solids content. An initial split is made at one end of the paper strip so clamps can be attached to each end of the split. The two clamps are connected via flexible bands to the splitting weights. Once the splitting weights are released the initial potential energy is transformed into kinetic energy. The difference between the initial potential energy and the kinetic energy is the total energy used in the splitting process. This last energy is composed of the splitting energy (cohesive and bending energy) and the friction energy loss of the apparatus.

Chapter Two provides a summary of the pertinent literature. A brief summary of the paper production process is presented first. The relation between the mechanical and chemical treatment of the pulp suspension and the consolidation of the paper and wet web strength development are discussed. The importance of filler, cationic starch, the retention system and the starch modified clay in the strength evolution of the sheet is also discussed. Previous studies related to the peeling of the sheet from rigid surfaces are reviewed and how these studies can be related to the paper splitting situation. Chapter Three describes the procedure for the pulp and chemical preparation, the sheet

consolidation, the paper splitter apparatus and how it operates. The calculation of the friction loss of the apparatus is also described. A brief review of the Instron tester is presented. Chapter Four of this thesis presents the paper splitting results. Cohesive and bending energy are calculated from the experimental results. The impact of the experimental variables on cohesive strength is described along with the correlation with the tensile tests. Calculations of sheet strain using relationships developed by Ostgerberg are also presented. These results are compared to strain obtained from Instron tensile tests. Chapter Five presents the conclusions of the research and how they can help for implementing modifications in paper machines. Chapter Six discusses recommendations for future work.

In this study the splitting energy of the paper was measured, this energy can be further divided in the bending energy and in the cohesive energy. It was found that the splitting energy behaves similar to wet web strength properties usually measured (tensile properties). From consistencies around 20% to consistencies near 55%, there is no significant growth in the energy. At 55% consistency an inflexion point occurs, and the energy starts to grow exponentially. Finally at consistencies around 88 to 92 % the splitting energy reaches its maximum value and a new inflexion point occurs, but in this case a sharp decrease in the energy results. It must be noted that splitting energy consists of both the cohesive energy holding the sheet together and the bending energy required to bend the sheet at right angles during the splitting test. The bending energy contributes to the peak in splitting energy. The effect of mechanical treatment can be clearly seen when comparing the pulp with freeness around 740 C.S.F. and the pulps with freenesses of 560 and 440 C.S.F.. In the former case a lower degree of cohesive energy is developed. The cationic starch addition results in an increase in the splitting energy. The addition of starch modified clay results in a stronger paper, when compared with the same level of

ash content obtained when normal clay was used. It is to be noted that the differences in splitting energy caused by the chemical additions, are more clearly seen as the consistencies increases. At low consistencies, between 20 and 55%, the differences are not as obvious.

CHAPTER 2

LITERATURE REVIEW

Paper Production Process

During the paper production process, the pulp suspension that is produced in the pulp plant is treated in the paper machine in a continuous way through several steps. The first one is called the stock preparation, which usually starts with the dilution of the high consistency stock in the discharge of one of the storage tanks, and ends with the blended papermaking furnish in the machine chest. During the stock preparation the fibrous raw material is mechanically and chemically treated in order to obtain a stable paper machine operation and a high standard of paper quality. Depending on the final use of the paper the mechanical and chemical treatment will be different. Among the most important treatments are the refining of fibers and the utilization of wet end additives. At the end the various fibrous and non fibrous furnish components are continuously combined and blended to form the papermaking stock. The next step is called the consolidation process, during this process the stock suspension is converted into a paper web with desired end use properties. The consolidation process is divided into the forming, pressing and drying processes; an additional calendaring process may also be included. During the forming process water is removed from the suspension up to the point where no more water can be economically removed using vacuum. During the pressing process additional water is removed by compressing the web several times between rotating press rolls. Then the remaining water is removed by thermal treatment until the final moisture content is obtained.

Wet Web Strength

In conventional paper machines, as soon as the sheet is formed in the forming section, and before it enters the press section, it is exposed to tensile stress when it is removed from the forming wire. The sheet is also stressed in all the open draws the machine has either in the press section or in the dryer section. The application of such a stress is necessary in order to overcome the force of adhesion between the wet web and the wire, the rolls, and the felts. If the tension is higher than the mechanical strength the wet web can withstand, a paper rupture may occur. In other cases paper delamination can also be a result of this external force. The higher the wet web strength properties, the less likely any of these problems will occur.

Traditionally the strength properties of the wet web have been characterized by the tensile strength and stretch, and different apparatuses have been used to measure these properties. The wet web strength determination is not a simple task, because the web is too weak to be able to support any significant applied force. The results obtained can therefore have considerable error. An additional problem is that there is no accepted laboratory procedure for preparing the wet webs or to modify the moisture content of the web.

In order to model the open draw effect, Mardon, Truman, Meadley and O'Blenes (1) developed a theory that was extended and modified by Osterberg (2) and that can be described by the following equation:

$$T_w = \frac{W_w}{1 - \cos\theta} + m_w V_w^2 \quad 2.1$$

Where:	T_w	=	web tension [N/m]
	W_w	=	work of separation [N/m]
	\emptyset	=	angle of take off
	m_w	=	mass of web per unit area [kg/m ²]
	V_w	=	wire speed [m/s]

As can be observed, the web tension required to peel the web from a surface will increase rapidly with the speed, and the tension necessary to overcome the sticking of the wet web to the wire or roll (work of separation) is dependent on the take off angle. If the web tension is greater than the tension the web can support a sheet break will occur.

According to Mardon and Short (3) the wet web strength depends on the following factors:

1. Fiber components: Chemical pulps have greater wet web strength than mechanical pulps. Hardwood has lower strength than softwood, and fibers with a higher content of hemicellulose also have higher strength
2. Fiber dispersion in the plane of the sheet (xy): The lower the basis weight the lower the strength. If the formation of the web is poor, lower strength will be achieved due to the presence of weak points

3. Fiber dispersion in z plane: The web is a layered structure, if components different than fibers separate the layers, the strength properties can change
4. Fiber orientation: If fibers are preferentially oriented in the machine direction, the wet web strength is higher in that direction
5. Moisture content of the sheet: The higher moisture content the lower the sheet strength
6. Specific sheet defects: All these defects lower locally the strength, affecting the overall performance
7. The extent of previous stretching: Reduces the load stretch property

There are other factors that alter the wet web strength and are not in the above list. Lyne and Gallay (4) showed how the beating time and the wet pressing affect the wet web strength properties. The effect of chemical additives also can contribute to the variation in the wet web strength.

Lyne and Gallay (5) explained, using unbeaten pulps and untreated glass fibers, how the strength develops with increasing the solids content of the web. In this study the solids were increased using air drying for water removal. It was concluded that two successive mechanisms, surface tension between the fibers and inter fiber bonding are the responsible of the strength increase. It may be considered that the net result of the surface tension is to bring together the fibers into closer contact, fiber entanglement, preparing in this way the web for the inter fiber bonding process. In the strength development curve, a discontinuity point can be seen, which shows when the change in

the main mechanism responsible for the strength development occurs (Figure 2.1). Up to 20 to 25% the strength increases through increasing surface tension forces. As water is removed more fiber-water-air interfaces are created where the forces of surface tension can act resulting in an increase of the fiber to fiber interaction and the corresponding increase in the web strength. After this point the effect of surface tension goes down and the fiber to fiber interaction becomes controlled by the forces between the fibers at a molecular level, the inter fiber bonding becomes the major factor in strength development and the strength increases with increasing dryness. It is to be noted that although one force dominates in each range, both forces are present during almost all of the process. In another study Lyne and Gallay (4) showed how the inflection point could be made to disappear by applying wet pressing by beating to a freeness below 100 C.S.F. ml. as seen on curves 4 and 5 of Figure 2.2. The study did not report the pressure that was applied in order to eliminate the inflection point. Considering the low freeness necessary to eliminate the inflection point one could expect pressures well above the normal used ones to obtain the same effect.

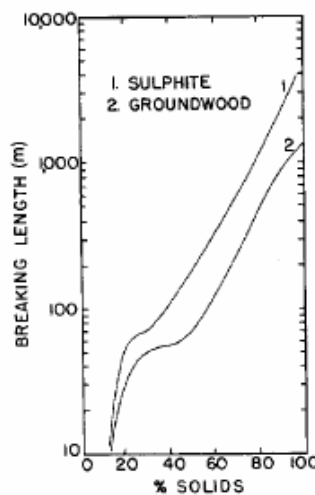


Figure 2.1 – Wet Web Strength Vs Solids (Lyne and Gallay, 5)

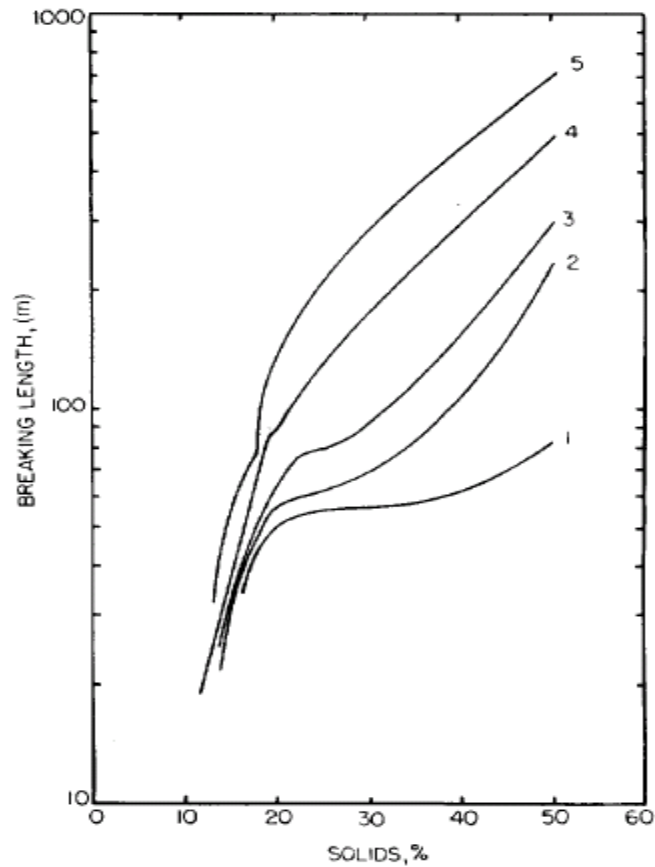


Figure 2.2 – Wet Web Strength of Refining Pulps Vs Solids (Lyne and Gallay, 5)

(Beating times in minutes: 1 – 0; 2 – 10; 3 – 20; 4 – 40; 5 – 60)

Brecht and Erfurth (6) used an improved stress-strain instrument for wet web properties measurements. With their research, plotting the results on a semi-log scale, an idealized shape of the tensile-dry content curve was proposed (Figure 2.3). Four zones can be visualized, the slope of the first one, up to 15 to 20% solids, can be attributed to inter fiber friction as the films of water between the fibers become thinner and the web contracts in thickness. In the second zone that goes up to 35 to 50%, air begins to enter the web, permitting the extension of surface tension effects from the outer faces of the

sheet into the interior, the slope is decreased due to the reduction of the water interfaces after the surface tension effects reaches its maximum. In the third zone up to 60 to 90% solids, the slope begins to increase more rapidly because inter fibrillar hydrogen bonding is accelerated as water is removed. Finally in the fourth zone, around 80% and up, the slope is caused by the usual increase in tensile strength with increased dryness. In this region the lower slope can be explained because the loss of moisture in the almost dry sheet stiffens the fibers and reduces the ability of some elements lying at a small angle to the stress direction to move and better support the applied force.

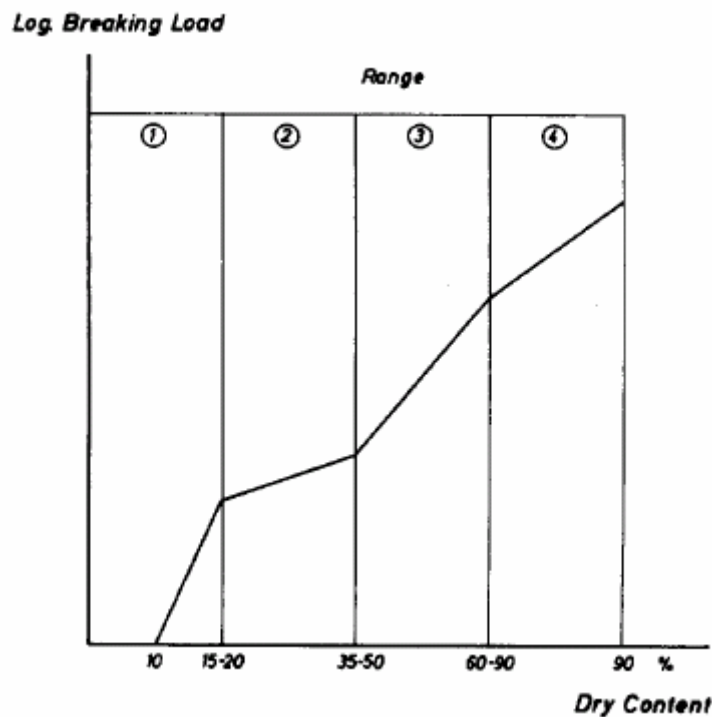


Figure 2.3 – Idealized Wet Web Strength Vs Solids (Brecht and Erfurth, 7)

In more recent studies Robertson (1966) and Rance (1980) obtained similar results to the ones obtained by Brecht and Erfurth. As shown in Figure 2.4, four zones

can be detected, where point A corresponds to the formation moment, point B is at air intrusion moment, point C is the first strength inflexion, and point D is the second strength inflexion. Baum (7), as seen in Figure 2.5, shows how the surface tension plays a major role in holding the wet web together, and bringing fibers closer until hydrogen bonds start to form, through a process known as the Campbell Effect (8) (Figure 2.6). The Campbell Effect is explained in a following section.

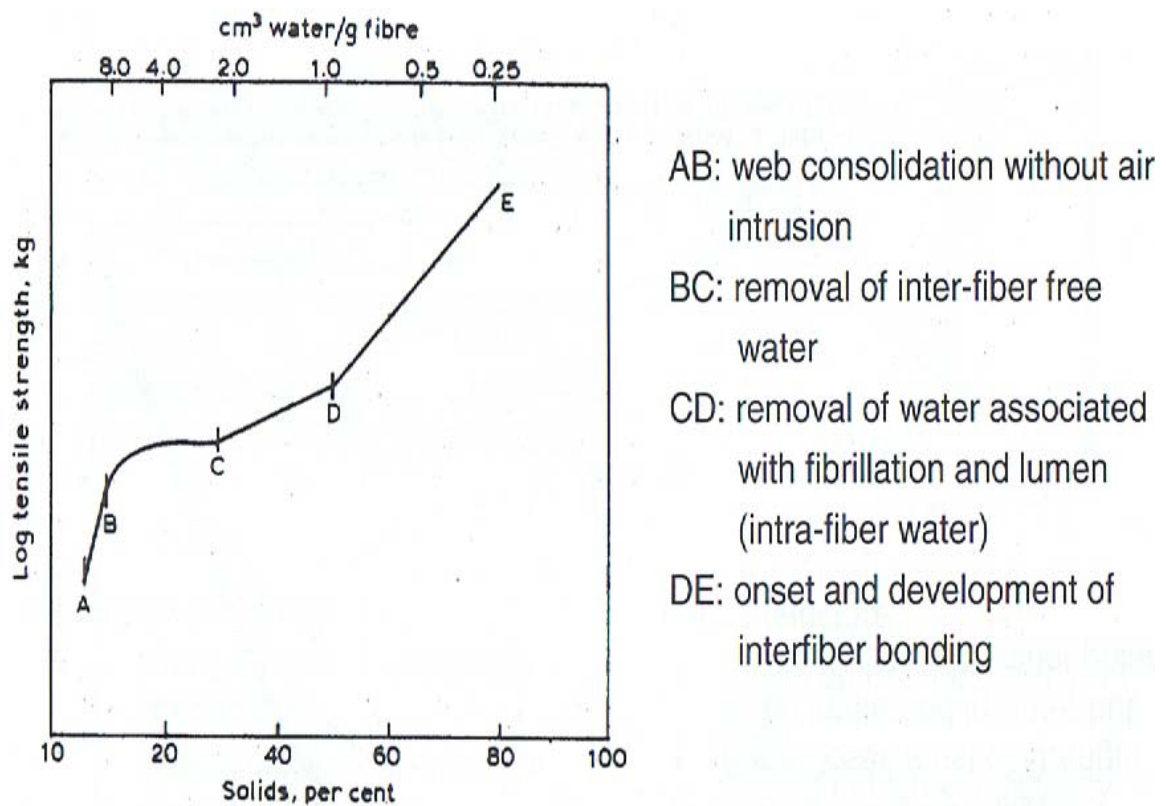


Figure 2.4 – Development of Wet Web Strength (Robertson, 1969)

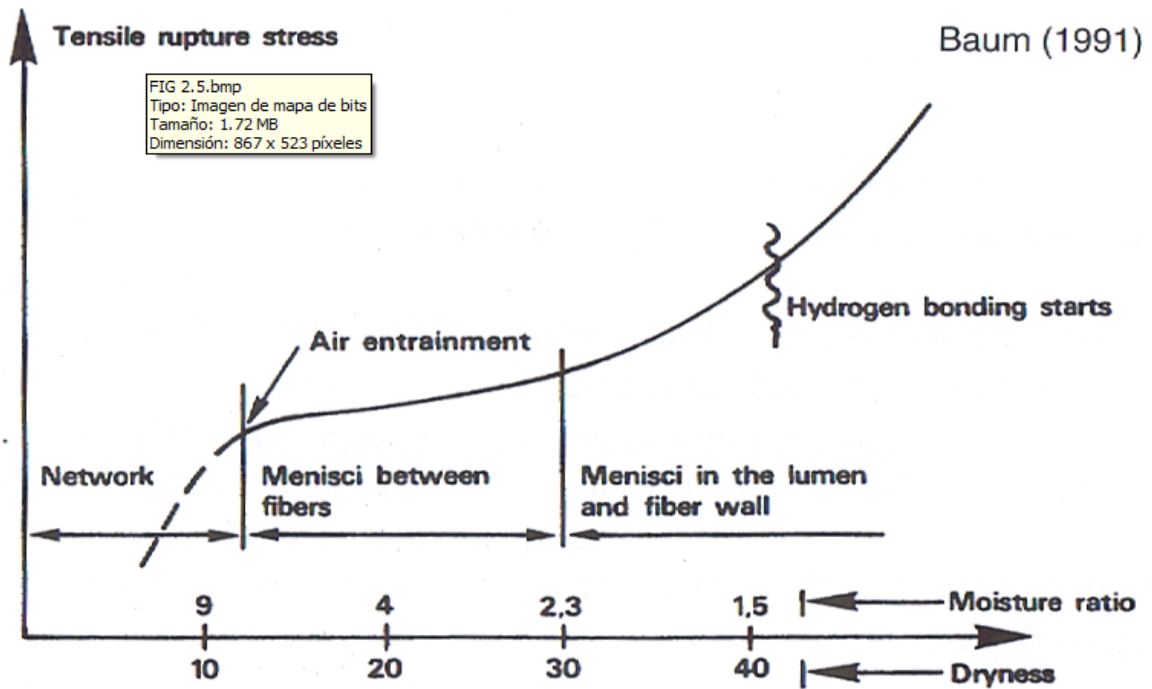


Figure 2.5 – Role of Surface Tension on Wet Web Strength (Baum, 1991)

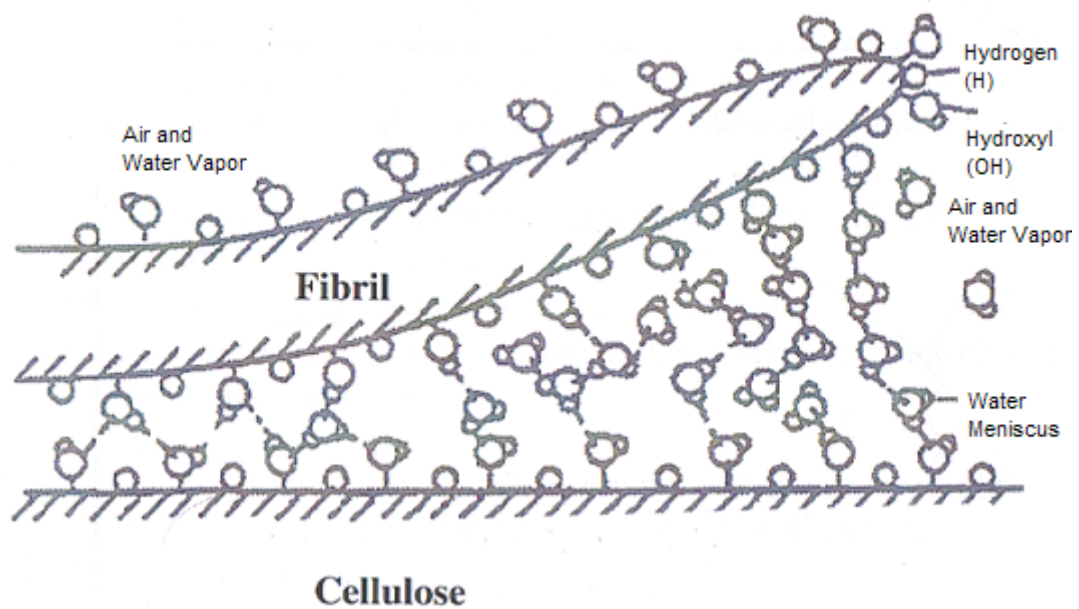


Figure 2.6 – Campbell Effect

The tensile strength of dry paper sheet formed using chemically pulped softwood can be described by Page's (9)

$$\frac{1}{T} = \frac{9}{8Z} + \frac{12C}{bPL_f RBA} \quad 2.2$$

Where:

T = tensile strength [Nm/g]

Z = zero span tensile strength [Nm/g]

b = shear strength of the fiber to fiber bond [N/m²]

P = fiber perimeter of the average fiber cross section [m]

L_f = fiber length [m]

C = fiber coarseness [g/m]

RBA = relative bonded area in the dry sheet

The fiber strength has little effect on the wet web strength as the fibers are not broken when stress is applied to the web. Then, for sheets of straight fibers weakly bonded (high moisture content), the fiber strength far exceeds the bond strength, and the equation takes the form of

$$T_{ww} = (bPL_f RBA_{ww}) / 12C \quad 2.3$$

Where: T_{ww} = wet web tensile strength [Nm/g]

RBA_{ww} = the proportion of the fiber surface that is contained within a water meniscus holding adjacent fibers together

Williams (10), takes into account that this equation could be used for considering the strength of wet web. Page (11), used the results obtained by Lyne and Gallay (4) to further develop this equation. He concluded that the shear force required to slide one fiber over another, for wet webs with solids below 30%, is $\gamma A \mu / r$, where γ is the surface tension of water, μ is the coefficient of friction between the two wet fibers, A is the area within the water meniscus over which the surface tension forces act and r is the radius of curvature of the water meniscus. Finally Page arrived at an equation for wet webs of the form of

$$T_{ww} = \mu \gamma P L_f RBA_{ww} / (12Cr) \quad 2.4$$

The problem with this equation is that it has several unknowns. For example the value of the RBA_{ww} is arbitrarily taken to be 0.5, for the coefficient of friction a value of 0.44 is taken from values for wet cotton fibers. If a more accurate value of the shear strength of the fiber to fiber bond (N/m²) for wet webs could be determined, the validity of the equation could be established. The problem is that it is not easy to measure this property for wet webs.

Although almost all the discussion has been related to the wet web tensile strength, it has to be noted that the wet web stretch is an important parameter governing the ability of the web to withstand the stresses in the draws of the paper machine. Usually the tensile strength level of the wet web is higher than the required to avoid a sheet break, however the web must be able to redistribute the stresses associated with the draws and this ability is related to the stretch of the web.

Some authors suggest that tensile strength is the best criterion when considering the runnability of the paper machine (12-15, 16). Others suggest that the stretch to break is the most appropriate criteria (15, 17, 18). Seth, Barbe, Williams and Page (19) suggest that having two sheets with the same stretch to break, the one with higher tensile strength will have a better runnability. Similarly, if two sheets have the same tensile strength, the one with higher stretch to break will run better. It has been proposed (19) to use both tensile strength and stretch curves to characterize the strength of a wet web. These curves are called the failure envelope curves. In Figure 2.7 the furnish B will run better than furnish A through all the solids content. When comparing the failure envelope curves from different mills using different furnish, it can be observed how the higher velocities are obtained in the mills with higher envelope curves.

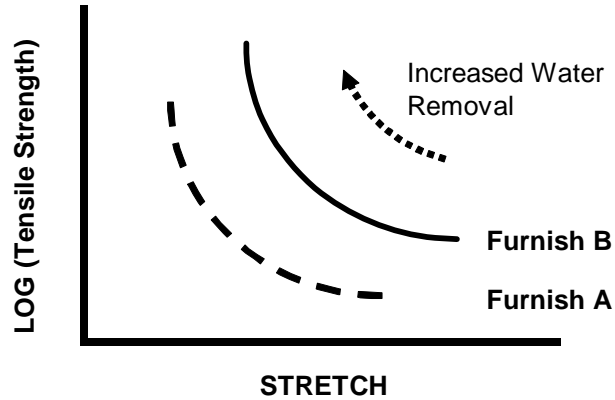


Figure 2.7 – Envelope Curve (19)

Surface Tension Mechanism

The consolidation process based on surface tension forces is called the Campbell effect. These forces give the wet paper its strength. Baum (7) explains how the surface tension consolidation process can be split into three stages. In the first stage, at solids content around 10%, the web is held together by surface tension forces arising from the menisci formed as the water layer recedes into the fibrous structure (Figure 2.8a). If the radius of curvature of the meniscus is large enough, the force that pulls the fiber together is given by $F = \gamma L$, where L is the length of the line of contact between air, water and fiber. As the water recedes into the fiber structure (around 12% solids), two meniscus are formed between adjacent fibers (Figure 2.8b), in this case the pulling force is given by $F = 2 \gamma L$. At about 20 to 25% solids, the water content of the sheet becomes so low that discontinuities in the liquid water film appear (Figure 2.8c). The pressure gradient caused by the surface tension forces depends on the thickness of the water film that holds the fibers nearly in contact. The pressure gradient is given by $\Delta P = 2 \gamma / X$, where X is the thickness of the liquid film. During this final stage, when the fibers are forced into

pressure of the order of 100 to 200 atmospheres as water is removed, is when the fibers are forced into close enough proximity that molecular bonds can start to form.

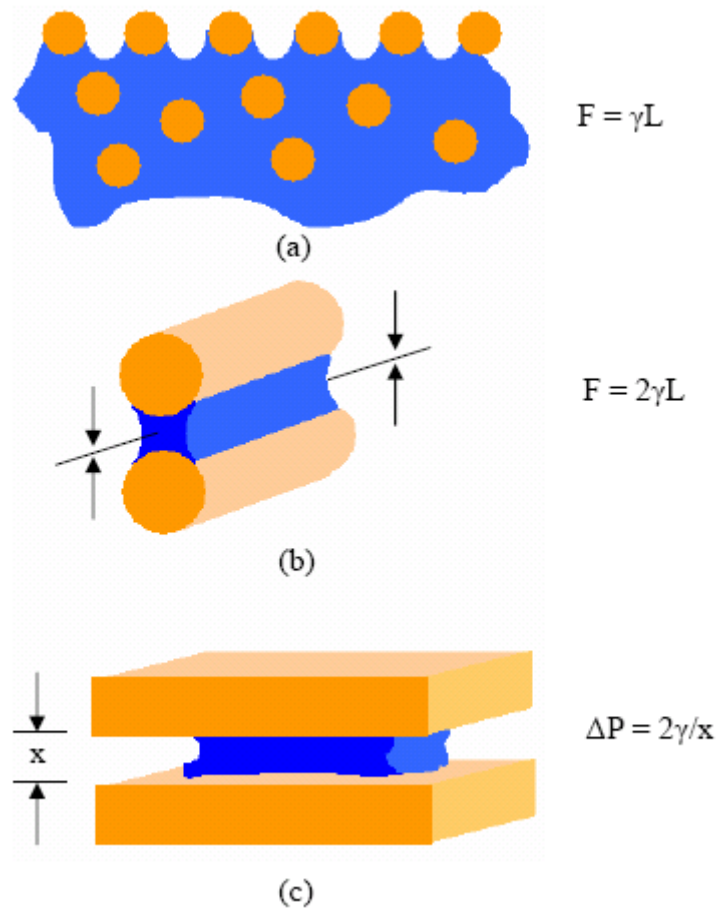


Figure 2.8 – Surface Tension Forces during Paper Drying

Inter Fiber Bonding Mechanism

The inter fiber bonding is closely related to most of the mechanical and optical properties of the paper. The number, area and strength of such bonds are among the key factors that determine the level of the above properties. The bonds can only be formed,

when the solids content of the paper increases during the production process. As stated by Campbell, the fibers are held close together by the effect of surface tension forces and as water is removed, the fibers can start to form bonds between them. There is a gradual change from the Campbell effect to the hydrogen bonding formation, which starts at around 50% of solids content.

There exist three different types of bonding mechanism:

1. Chemical bonds within cellulose molecules and acid-base interactions between them. For the fibers, the hydrogen bonding is considered to be the main source for bonding. The bonding energy ranges from 8-32 KJ/mol and depends on the surrounding molecular structure
2. Intermolecular van der Waals bonds: have a smaller bonding energy (25% of the hydrogen bond energy), but act in all directions and can contribute to the cohesion of the paper web
3. Entanglements of polymer chains: mechanical interlocking process

The inter fiber bonding occurs in the zone where two fibers are so close together that any of the above types of bonding may occur. External fibrillation and fines in the interface aid the formation of these kinds of bonds by linking the fiber surfaces more closely together during the Campbell process. The external fibrils and fines significantly increase the total fiber surface area.

Strength Development and Mechanical Treatment

During paper production the main mechanical treatment process is pulp refining. The objective of refining is to improve the bonding ability of the fibers so that they can form a strong paper sheet that will not cause problems during the production process and to produce a sheet of the desired properties.

Refining affects the fiber in many ways such as (20):

- Cutting and shortening fibers
- Fines production removing parts from the fiber walls
- External fibrillation
- Internal fibrillation or swelling
- Internal changes in the wall structure, such as delamination
- Curling (high consistency) or straightening (low consistency) of the fiber
- Creating nodes, kinks, slip planes, microcompressions in the cell wall
- Redistribution of hemicelluloses from interior to exterior of the fiber

All the above factors affect the bonding capacity of the fiber. As beating increases, the fibers become more flexible and more easily collapsed resulting in increased bonding surface area. The production of fibrils also plays an important role for strength development. If these properties were obtained without the internal rupture of

the fibers, the final strength properties would be lower. This was shown in an experiment performed by Smith and Murphy (21) with viscose fibers, where the fibers were subjected to water pressure that made them swell, without internal fibrillation, but at the end no strength was developed. The existence of fibrils causes the Campbell pressure to become greater because the fibrils can come into closer contact. As a result there is greater fiber to fiber bond area and an overall increased level of bonding.

Da Silva (22) found that wet web strength properties develop linearly with beating-energy consumption, contrary to the nonlinear curve obtained when wet web tensile strength is plotted versus freeness. He also concluded that the swelling and delamination of the cell wall are critical for sheet consolidation, fiber to fiber bonding and that the presence of fines significantly increases wet web tensile strength. The effect of refining result, for the same refining treatment, depends on the flexibility of the fibers, thickness of the cell walls, packing density of the cell walls, S₂ fibrillar angle and chemical composition of the fiber essentially hemicelluloses. The hemicelluloses interact strongly with the water and promote the fiber swelling during the refining, in addition they participate in the inter fiber bonding by contributing hydrogen bonds. Da Silva also found that the wet web stretch develops linearly with beating-energy consumption.

Refining not only increases the wet web strength, it also increases the wet web stretch, since the fiber curl and microcompressions are better utilized due to increased fiber to fiber interaction. Previous studies (23) have shown that the induction of curl, kinks and microcompressions in the fibers, through high consistency refining treatment (consistencies around 30 to 35%), can produce a very large increase in the wet web

stretch, especially at low solids. The problem is that this increase in stretch is accompanied by a decrease in wet web tensile strength.

Strength Development and Chemical Treatment

The main objective of the chemical treatment during the paper making process is to use wet end additives that help to achieve the paper properties set by the customers and enhance the paper machine runnability. The chemical additives can affect the following paper properties (24):

- Structural: Basis weight, formation, porosity, etc.
- Mechanical: Tensile, bursting, internal bonding and surface strength, tearing resistance, stiffness, etc.
- Appearance: Color, brightness, opacity, gloss
- Barrier and resistance: Sizing
- Permanence: Durability, color reversion, chemical stability

Other types of chemicals are used improve the drainage, minimize entrained air and foam, keep machines clean and retain other additives in the paper. If the wet end chemistry is not well designed and balanced, the chemicals that initially were added for positive results can produce machine deposits, scale and foam spots, reduce drainage and pressing efficiencies, and all the positive results desired in the final paper can be reduced or eliminated.

The trend toward increasing machine speeds, producing lighter paper with the same strength properties, increasing the filler content to replace fiber and optimizing chemical consumption, has increased the attention on the management of wet end chemistry.

Pikulik (25) using Page's equation 2.4, considered the Campbell effect and the importance of the surface tension during the early part of the web formation concluded that any reduction in surface tension of the white water (around 72 mN/m) results in a lower strength of the wet web, at least in the zone where the surface tension is the dominant mechanism. Surface active chemicals, such as soap of fatty and resin acids extracted from wood or the lignosulphates from the pulping process lower the surface tension of the water considerably, thus highlighting the importance of a good washing process for the pulp before it enters the paper machine. Additionally, almost all the chemicals currently used in the wet end also lower the white water surface tension. One of the important objectives of the wet end chemistry is to control the chemical addition so the surface tension is not unnecessarily reduced.

Laleg, Ono, Barbe, Pikulik and Seth (26) showed how a small amount of cationic starch increased the white water surface tension, they explain this by a possible complex reaction between the starch and other surface active materials which result in a deactivation of the surfactant ingredients. When the starch addition was further increased, the surface tension of the water went down.

The chemicals that reduce the surface tension the most are the so called surfactants. These materials are widely used during the paper process to improve the pulp washing, for softening of the paper, as defoaming and antifoaming agents, to improve the absorbency of the paper, to control deposits, to wash and condition the felts, and as corrosion inhibitors.

Other wet end additives include fillers, dry strength and wet strength additives. Fillers and other materials can interfere with fiber to fiber interactions and interrupt the capillaries of water that reinforce the wet webs thus lowering its strength. The dry strength additives (such as starch) only have an important effect when the solids content is above 60%. Wet strength additives, requires the formation of covalent chemical bonds that usually can be only formed at high temperatures that exist in the dryer section, so their importance for wet web strength is not relevant.

Pikulik (25) stated that for a chemical to be able to increase the wet web strength, it has to be able to crosslink the fibrous network, even in the presence of water. It is not easy to design such a chemical considering that the only chemically reactive groups that can be used for this purpose are the hydroxyl groups, -OH. However in the wet web there are many more of these groups available from water molecules than those from cellulose. Thus any chemical additive reactive towards the -OH groups has a greater chance of reacting with water than crosslinking the fibrous network. Recently several polymers capable of increasing the wet web strength have been identified. Among them is the cationic aldehyde starch that improves the wet web strength of webs formed with chemical fibers (27, 28). Also a product called Chitosan and other polymers containing

the primary amino groups can increase the strength of wet webs made from mechanical pulps (29).

Fillers

For many paper grades mineral fillers are the second most important component in the paper furnish. One of the main reason for using fillers for the paper production is the reduction in the furnish cost, while also reducing the energy consumption (especially during the drying process), and increasing the paper machine production capacity. The fillers also improve other properties such as (24):

- Formation and sheet structure: Filling sheet voids
- Appearance properties: Brightness, opacity, whiteness, gloss
- Texture and feel: Smoothness
- Printability: Smoothness, opacity
- Dimensional stability

There are different type of fillers, including Titanium dioxide, Kaolin clay, Talc and Calcium carbonate. Filler selection depends on the properties to be improved and the final quality of the paper. Although most filled paper are produced for the printing and writing, in recent years there has been an increased use in package board, newsprint and tissue paper.

The main problem associated with the filler increase is the reduction in the strength capacity of the paper, not only in the final state, but also during the paper production. To be able to increase the amount of filler used during paper production, several options can be considered. One is the use of dry strength additives, such as modified starch. Other methods such as pre-floculation of the filler, modification of the fillers, synthesized fillers with different structures and chemistries, polymer treated fillers, lumen loading and multi-layer forming have been explored (30).

Starch

Is the most common dry strength additive. Starch is not only used as dry strength additive, it also is used as a filler retention agent, drainage agent, as an emulsifying aid for synthetic sizing materials and as the cationic component of multiple-components retention systems. Starch additions range from 0.25 to 2.5% of the total solids content. Because the retention of unmodified starch, which enhances attachment to the negatively charged fibers, is low (below 40%) it is necessary to attach cationic substituents to it. The cationic starch improves the web strength by enhancing the inter fiber bonding because it can participate in forming hydrogen bonds with the fiber surface cellulose molecules and can increase the number of hydrogen bonds that would naturally occur in the bonded area between two fibers (Figure 2.9).

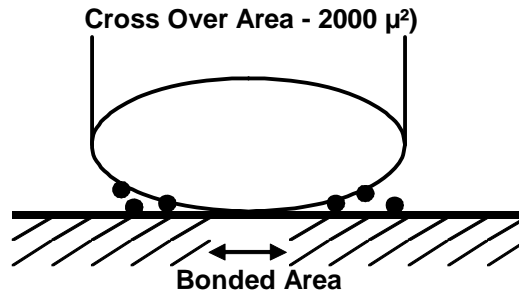


Figure 2.9 – Dry Strength Additives Improve Bonding

Starch does not distribute equally among all the components of the paper stock furnish. It tends to adsorb more on high specific surface area components such as fillers and fiber fines. Thus, fillers and fines end up with more starch than the fiber itself and consequently there will be less starch available to enhance fiber to fiber bonding when high levels of fillers are present.

Retention

During the paper production chemicals are added to increase the retention of fiber fines and mineral fillers. At the same time these chemicals also improve fines retention and improve the water drainage during the formation process. These retention chemicals are polymers with a range of molecular weights (low, medium and high), and different charge densities (low, moderate and high). Retention is enhanced through several possible mechanisms (20) which include.

1. Agglomeration/Coagulation: The attachment of the small particles in a furnish to the large fibers and their retention with the fibers
 - i) Charge neutralization: Uses the addition of an electrolyte or a very low molecular weight high charge polyelectrolyte. Typically alum or polyaluminum chloride (PAC) is used for this purpose (Figure 2.10)
 - ii) Patching: The polyelectrolyte has high charge density and low to medium molecular weight, such as modified polyethyleneimine, polyamines, and polyamideamine epichlorohydrin resins (Figure 2.11)
 - iii) Heterocoagulation: Is the aggregation of unlike particles by one of the first two mechanism
2. Flocculation
 - i) Bridging flocculation: The gathering together of the small particles in a furnish into a macroparticle (floc) and their retention in the interstices of a web as it is formed. Uses the addition of high molecular weight and low charge density polyelectrolytes (Figure 2.12)
 - ii) Network flocculation: Two or more polymers react together in a first step to form a polymer network. This network entraps the particles mechanically

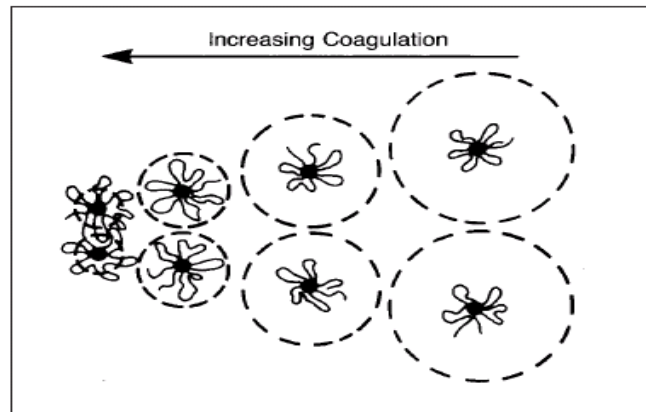


Figure 2.10 – Charge Neutralization

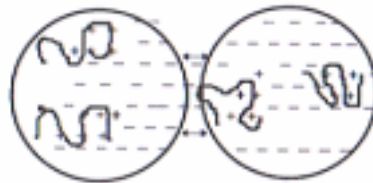


Figure 2.11 – Patching Mechanism

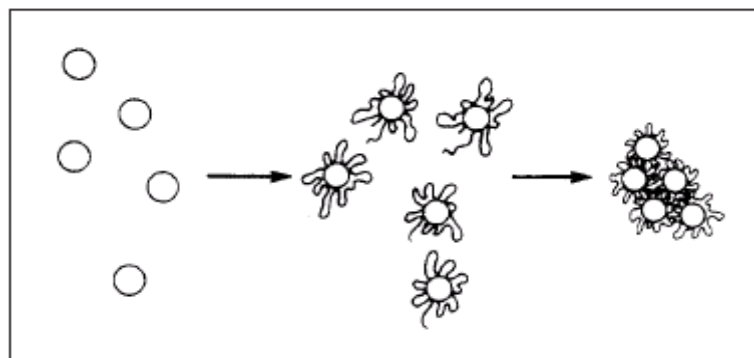


Figure 2.12 – Polymer Bridging

Retention Systems

Depending on the desired results, an initially simple system can be transformed into a very complex one. Several different kinds of retention systems are described below:

1. Single cationic polymer systems: High molecular weight, low charge density polyacrylamides (PAM). The addition levels are between 0.2 to 3 lbs/ton
2. Dual component systems (A): Anionic or cationic polymer plus aluminum. The alumn (also cationic starch, PAC and polyamine can be used) is added first and then a high molecular weight A/C-PAM
3. Dual component systems (B): Cationic polymer plus anionic polymer. A low molecular weight, high charge density cationic polymer (branched if possible) and one high molecular weight, low charge density anionic polymer are used. The cationic polymer is followed by the anionic one
4. Microparticle systems: A microparticle (silica or bentonite) is used in conjunction with a natural (cationic starch) or synthetic polymer (high molecular weight A/C-PAM). This is applied prior to the last point of high shear (usually the screen before the head box). The microparticle is applied after the screen

Starch Modified Clay

Recently, fillers have been produced which are coated with starch as a result strength improves. This potentially provides a method to overcome the limitations on

clay addition. The starch addition in the wet end can result in better sheet strength, however the amount of starch that can be added is limited. Cationic starch has a higher cost and its retention depends on the level of anionic trash in the pulp. Higher amounts of starch can cause formation problems as well. If starch retention is not controlled, unretained starch can create pitch, slime, and sticky problems. To overcome this situation a method for the modification of PCC or clay fillers with coated starch gel was proposed (31). The results showed a significant improvement on the sheet strength when this modified filler was used. To further improve the strength, a method to make the starch less soluble after being coated on the filler surface was created (32). The starch-coated-clay created has a relatively large size with a fibril shape, thus the particles can be easily entrapped by the fiber network to increase the retention. The low solubility of the starch also increases its retention in the wire, and less starch goes with the white water, eliminating the problems that this situation causes.

Strength Development and Web Consolidation

The properties of the wet webs strongly depend on the procedures used to remove the water during the consolidation process (33, 34, 35). In these studies it is also clear that the wet web strength not only depends on the moisture content but also on the procedure by which the moisture content is obtained. Seth, Barbe, Williams and Page (19), developed a procedure in which great effort was invested in producing specimens formed under similar drainage conditions and dewatered under reproducible procedures so that comparison when changing the furnish components could be made. They also confirmed how the wet strength, for the same solid content, increased by 50% when comparing two set of handsheets. In one condition (the stronger case) only a single wet pressing stage was applied, while in the other two consecutive stages were applied. The

first case was chosen and by changing the pressing pressure they could test specimens between 15 to 55% of solids content. The specimens were tested using a conventional Instron universal tensile testing machine, under this conditions they are held vertically during the test, water migrates due to gravity and the load is affected. These effects were examined and found to be negligible for the wet web solids considered. Horizontal testing was not considered necessary.

There exist two theories on how to compare modifications in the wet web. The first theory is that webs should be compared at similar solids contents, the second is that webs should be compared similar specimen preparation conditions (36, 37, 38). The first approach finds its justification because in the actual production process, the moisture content of the paper generally remains constant at the different points along the paper machine. The second approach considers that the solids content of a sheet depends on the response of the furnish to the drainage and the machine operating conditions.

Forming

The objective of forming is to deposit a dilute suspension of fibers, fines and fillers, uniformly onto one or between two forming fabrics. The water is the removed by forces generated between the fabrics, or by suction developed by different drainage elements. At the end of this stage the web is still weak and wet, only minimal consolidation has occurred. During the early steps, the vacuum produced by the drainage elements provides the suction necessary to remove the water. As the wet gets dryer, progressively increasing vacuum levels are applied with the help of vacuum legs and low vacuum pumps. As the machine speed goes up, the time available for the dewatering

process is shorter and the water removal is more difficult to accomplish. The drainage elements become less efficient and the web leaves the couch containing more water than in a slower machine (39). The solids content can go down from 20%, in the traditional machines, to 12 - 14% in some modern twin formers (40). Despite the lower solids content it has been shown that the web can be effectively pressed without affecting the quality of the paper (41).

Pressing

The web that comes from the forming section is compressed in one or more rolls or shoe presses. In each press either one or two press felts are used to receive water from the sheet. If multiple presses are used, higher press loads are used with each successive press (20). The solids content at the end of the press section is around 40 to 45%. During pressing, the contact between the fibers is improved, yielding higher RBA and as a result the wet web strength is increased.

Drying

The final water removal step is drying. This is accomplished by circulating the paper around steam heated cylinders. The sheet is held against the steam cylinder by a dryer fabric which is under tension. The pressure with which the sheet can be held against the cylinders is limited by the tension in the dryer fabric and the radius of the cylinder. Along with other factors this limits the maximum attainable drying rate. If the drying rate could be increased, compact and shorter machines could be constructed (42). During the drying process, the shear stresses (produced by the shrinkage of the fibers in the lateral direction) at the inter fiber bonds form microcompressions, that modify the

mechanical properties of the bonded segments and the final paper performance. Most of the papermaking bonds which link fibers, fines and fillers are developed during the drying process, consequently the dry paper strength can be ten or more times greater than the pressed wet web strength.

Wet Web Cohesive Strength

As can be seen from equation 2.3, the tensile strength is dependent on the shear strength of the fiber to fiber bond. To solve equation 2.3, when the surface tension is the dominant mechanism, Page related the strength of the fiber to fiber bond to the shear force required to slide one fiber over another ($\gamma A\mu/r$) and approximated the value of the coefficient of friction (μ) to one obtained from wet cotton fibers, he also assumed a value of 0.5 for the RBA. In this way he obtained values for tensile strength that agree with many values found in the literature for wet webs at 30% solids. The standards methods for measuring the internal bond strength, described by Tappi T 541 (Internal Bond Strength of Paperboard (Z-Direction)) and Tappi T 569 (Internal Bond Strength (Scott Type)), requires the application of a pressure sensitive tape to the sheet surface. This can be easily done for dry sheets, but in even slightly damp sheets, the presence of water degrades the adhesion of the tape and makes the test impractical for wet sheets.

A better approach could be obtained if the cohesive energy that held the fibers together could be directly measured from the wet web at different moisture contents. Patterson and Taylor (43) designed and created a new apparatus, a paper splitter, which is able to determine the energy needed to overcome the cohesive strength of a paper sheet. The main advantage of the apparatus is its ability to test sheets over almost the entire

range of moisture contents that are present on a paper machine. In this device, falling weights are used to supply the force needed to split the sheet. The data recorded by the instrument while the sample is being split, are used to calculate the difference between the kinetic energy and the potential energy of the falling weights. This difference is closely related to the energy needed to split the paper.

Previous works have dealt with the issue of separating a wet web from rigid surfaces such as wires and press rolls. Among the first investigators were Mardon, Truman, Meadley and O'Blenes (1) and Osterberg (2) who developed equation 2.1, considering the case for an inextensible web, solving equation 2.1 for W_w we have:

$$W_w = (T_w - m_w V_w^2)(1 - \cos\theta) \quad 2.5$$

In this equation the work (W_w) and the tension (T_w) are in units of N/m, the mass (m_w) is in kg/m² and the velocity (V_w) in m/s. The equation is solved by calculating the power required by the web (moving at a velocity V_w) to separate from a static surface (Figure 2.13). This power is consumed by the kinetic energy increase and the energy used in doing work (W_w) on the paper. Mardon (44) also considered the situation when the web stretches as it separates from the base, then following the same procedure he arrived to equation 2.6.

$$W' = (T_w - m_w V_w^2)(1 - \cos\theta) + T_w \epsilon - m_w V_w^2 \epsilon (1 - \cos\theta + \epsilon/2) \quad 2.6$$

Where W' is the total work done on the paper and ϵ is the strain of the web. Mardon studied the case when the separation point was stationary and the solid surface moves at a velocity V_w , this case is similar to the situation in the paper machine. The equation obtained considering this situation is identical to equation 2.6.

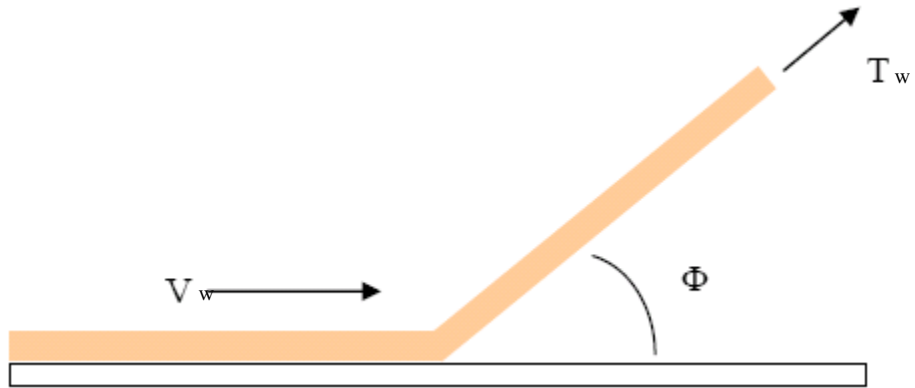


Figure 2.13 – Web Separation from Solid Surface

Osterberg (2) using vector analysis studied the same situation and arrived to equation 2.7

$$W_T = (T_w - m_w V_w^2)(1 - \cos\theta) + T_w \epsilon + m_w V_w^2 \epsilon \cos\theta \quad 2.7$$

In this case W_T (Osterberg total work done on the paper) is made up of three parts: work of separating the two surfaces (W_S), work of extension (W_E) and work involved in increasing the web's moment of inertia (W_M).

$$W_T = W_S + W_E + W_M \quad 2.8$$

These terms are defined as

$$W_E \approx T_w \epsilon / 2 \quad 2.9$$

$$W_M = m_w V_w^2 (\epsilon + \epsilon^2 / 2) \quad 2.10$$

And solving for W_S in equation 2.8 yields equation 2.11

$$W_S = (T_w - m_w V_w^2)(1 - \cos\theta) + T_w \epsilon - m_w V_w^2 \epsilon(1 - \cos\theta + \epsilon/2) - T_w \epsilon/2 \quad 2.11$$

The equation found by Mardon and Osterberg can be related by:

$$W_T = W' + W_M \quad 2.12$$

During the splitting test the work required to separate the paper from the same paper is measured. The situation can be approximated by equation 2.11, considering that during the test the take off angle is 90° (Fig. 2.14), this equation reduces to:

$$W_S = (T_w - m_w V_w^2) - m_w V_w^2 \epsilon(1 + \epsilon/2) + T_w \epsilon/2 \quad 2.13$$

From the experiment the tension, velocity and mass are known. The work of separation (W_S) can also be calculated, but to be able to compare the experimental results with equation 2.13, it is necessary to measure the strain of the wet web, which is something the apparatus is not designed to do, although approximate measurements between zero and two percent have been made (44).

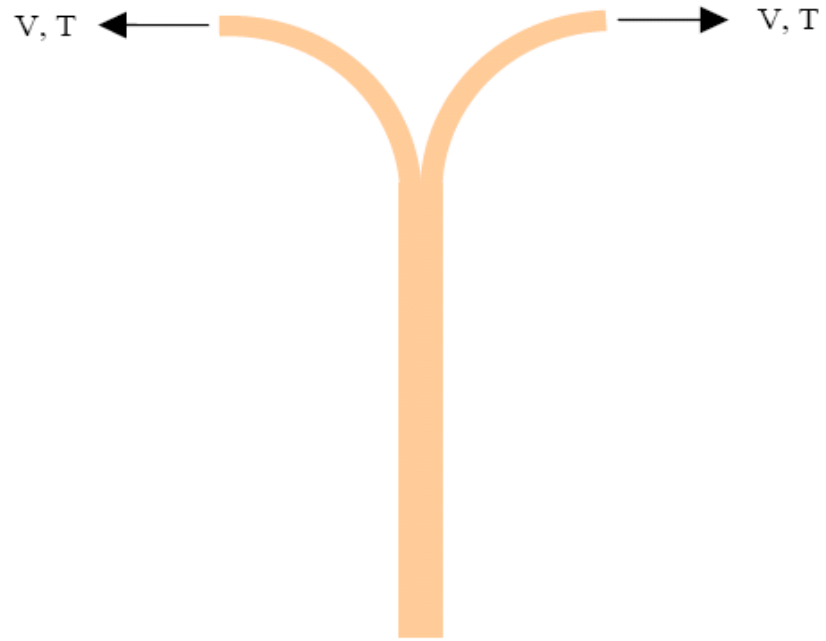


Figure 2.14 – Velocity and Tension during Paper Splitting Process

CHAPTER 3

EXPERIMENTAL PROCEDURES

The experiment was designed to simulate the dewatering processes the paper is subjected to during its production. The sheets were formed using a Formette Dynamique. The wet web solids after forming were around 18 to 22%, similar to the solids obtained at the couch roll of a Fourdrinier machine. The sheet were then pressed resulting in a solids content of 38 to 42%, which is similar to that obtained after the press section in a paper machine. Finally heat was applied using a drum dryer to obtain solids contents in the range of 50 to 95%. The web production process was similar for all the cases, allowing comparisons between the different treatments performed on the pulp suspension.

Pulp Preparation and Mechanical Treatment

A bleached softwood kraft pulp supplied in dry lap form was used to produce the paper sheets. The pulp was refined according to Tappi method T 200 (Laboratory Beating of Pulp (Valley Beater Method)). Each batch of pulp was prepared using 5 lb of pulp. The Valley Beater was run for 10 minutes with no weight applied to disintegrate the pulp. The consistency of the pulp suspension was 1.4% and the initial freeness was 780 C.S.F.. The freeness level was determined using Tappi method T 227 (Freeness of Pulp (Canadian Standard Method)). The beater was operated for different amounts of time in order to obtain three levels of refining. For the first level the freeness was around 740 C.S.F., indicating a slight mechanical treatment performed on the pulp. In the second condition the freeness obtained was between 540 to 560 C.S.F. and in the final

high mechanical treatment case the freeness level was around 440 C.S.F.. After the mechanical treatment, the fiber suspension was stored in a refrigerated room for less than one week, prior to being used to form the test sheets.

Chemical Preparation and Chemical Treatment

The chemicals used during the experiment were: clay (provided by Imerys), cationic corn starch (provided by ADM), C-PAM (provided by EKA) and starch modified clay (provided by Imerys). The first three chemicals were obtained in powder form while the last one was a slurry at solids content of 70%. The powder chemicals were prepared and used the same day the sheets were formed. All the chemicals were diluted with water until reaching 25% solids for the clay, 1% solids for the cationic starch, 0.5% solids for the C-PAM and 25% for the starch modified clay. Once diluted, they were kept under agitation to ensure an even dispersion of the suspension. The clay and the starch modified clay have a strong tendency toward sedimentation, in these cases it was extremely important to provide a good agitation, otherwise the suspension would not have an even distributed concentration. The C-PAM was prepared using a magnetic agitator. This chemical preparation requires great attention because it can easily form flocs which can affect the retention performance and the evenness of the solution concentration. Before adding to the stock, it is necessary to agitate the suspension for more than 30 minutes, this allows enough time for the polymer chains to straighten. The diluted cationic starch was stirred and slowly cooked for 50 minutes until the mixture reached a temperature of 92°, then the temperature was kept at this level for 25 minutes, after which the heat was removed and dilution water was added to reduce the temperature and the solids content to 0.5%. Enough C-PAM and cationic starch was prepared at the

beginning of each day to be used in the corresponding sheets, excess amounts were discarded.

Once prepared, and depending on the case to be evaluated, the chemicals were added as follows

1. The refined pulp suspension initially at 1.4% of consistency, was diluted to obtain a consistency between 0.5 and 0.7%
2. Once measured, the required amount (ml) of clay or of starch modified clay (depending on the case), the suspensions were additionally diluted with 8 liters of water before adding them to the pulp furnish. A final chemical concentration of around 0.5% was obtained
3. The required amount of C-PAM and the C-Starch were also measured (depending on the case) and then diluted adding 5 liters more of water to each suspension. The final concentration for the C-PAM was below 0.005% and for the C-Starch was below 0.04%
4. The chemicals were added in the following order:
 - i) Clay or Starch Modified Clay: Wait for two minutes for suspension dispersion before adding the next chemical
 - ii) Cationic Starch: Wait for one minute before the next chemical addition
 - iii) C-PAM: Just before adding the fiber stock to the Formette holding tank. 0.1 kg/ton of product was added every time clay or starch modified clay was added

The same basic procedure was followed for all the sheets. The additional dilution of the chemical was required to ensure a well mixed furnish and to allow the chemicals to have the ability to evenly react between each other and with the fibers and fines.

The ash content in the webs were measured using Tappi method T 211 (Ash in Wood, Pulp, Paper and Paperboard: Combustion at 525 °C).

Web Formation

Once in the Formette holding tank, the pulp furnish was ready to be transformed into a web. To be able to produce webs with similar conditions the equipment (Figure 3.1) was operated in all the cases following the same procedure:

1. The pulp consistency was below 0.8% in order to obtain even formation and to avoid pipe and nozzle plugging. In addition to working at consistencies lower than 0.8% it is necessary to:
 - i) Keep all the pulp storage tanks clean and closed
 - ii) Always prepare the furnish necessary to produce one sheet at the time
 - iii) Before adding the furnish to the holding tank, the agitator should be working, otherwise the fiber may settle and plug the system
 - iv) When there is no more furnish in the tank add water and let the equipment work for 20 more cycles, before starting the dewatering process. With this

step one can be sure that no fiber will remain in the system to plug it while not working. The formation is also improved

- v) Once the sheet is formed and taken out from the equipment, add water to the holding tank and start the system as if normal operation to flush the system
 - vi) Work the system in manual mode
 - vii) At the end of the day the equipment should be completely cleaned to avoid any remaining fiber to dry and cause problems in the future
2. Two regular forming wires (one over the other) were adapted to be the support of the fiber mat during the formation process. With this configuration one wire helps as a support for the wire that will finally support the fibers
 3. The rotor velocity was set to 900 RPM during the wet formation and increased to 1500 RPM during the dewatering process. In this way the solids at the end of the process is in the range of 18 to 22%
 4. The nozzle at the end of the pulp pipe should always remain at the same angle when measured against the forming surface. In this case the nozzle jet was perpendicular to the equipment front face
 5. The pulp pressure was set to 1.6 bar



Figure 3.1 – Formette Dynamique

At the end of this stage, the web consistency was between 18 to 22%, depending on the basis weight of the web. The low consistency corresponds to the higher basis weight webs (300 and 400 g/m²).

Before starting the formation of the sheets to be tested in the splitter and Instron tester, several sheets were prepared to calibrate the system and to determine the consistency through the entire web. The idea was to establish the amount of dry pulp

required to form a sheet of a certain basis weight and to identify if the pulp was evenly distributed through the whole sheet. Some problems were found and corrected.

After formation all the wet webs were trimmed to remove the wet borders. If the web did not require any other treatment, they were stored in fully sealed plastic bags and placed in the refrigerator until the strips formation time arrived. This process was accomplished usually in the following two days. The paper was cut into strips 2 inches (5.08 cm) wide by 22 inches long (55.88 cm), obtaining 12 strips per sheet. These strips were again stored in a fully sealed plastic bag for 5 days until testing started. When making the sheets, samples were taken to measure the basis weight content of each sheet.

Web Pressing

As previously stated, the consistency going out from the forming section can be as low as 18%. When a web with such a low consistency is pressed, the web can be severely damaged and ribbing problems can appear. To avoid this, all the sheets were subjected to a preliminary pressing step. During this intermediate step, the web was placed between two blotter papers and with the help of a manually operated roll pressure was applied to dewater the sheet even more. The procedure was repeated, using new dry blotter papers each time, until no more water was removed from the wet web. At this time the paper could go safely through the pressing stage.

The wet web pressing was accomplished in a laboratory press, formed by two rolls, one fixed to the frame structure and the other joined to two air actuators (Figure

3.2). The air pressure applied to the actuators was always the same, 3 bars. To determine the pressure effect in the wet web, two conditions were tested, the first one with only a single press stage and the other with two press stages. In both cases blotter paper was used as the water receiver in both sides of the sheet. The consistency obtained for the single step case was around 38 to 42%. When the wet was pressed a second time using new blotters, the consistency increased by 5 to 7% percentage points raising to a range between 45 to 49% of solids content. The single step was chosen as the standard procedure due to its close relation with the results obtained in a real paper machine.



Figure 3.2 – Lab Press

As was done with the formation process, several sheets were prepared to calibrate the system and to determine the consistency at different points in the CD and MD directions. Significant variations in consistency across the web CD were found, the cause of them were found and corrected. If the pressed paper did not require any further treatment, the wet webs were stored in fully sealed plastic bags and placed in the refrigerator.

Web Drying

To dry the wet webs, a drum dryer was used (Figure 3.3). This equipment is similar to a dryer roll in a paper machine, it includes a forming fabric to press the sheet against the hot surface of the roll. The only difference is that it is composed of a single dryer and for our case it was necessary to operate it at low speeds. Several calibrating sheets were also prepared and evaluated before the actual testing sheets were formed. The idea was to obtain enough knowledge on how the dryer velocity and time affected the final web solids. This was one of the crucial processes of the entire experiment, because the idea was to obtain several points of solids through the range of 55 to 95% (at least 4 points: 55, 70, 85 and 95%). The intent was to never apply water to reduce the solids content. When water was sprayed onto the dry sheet surface in order to reduce the web solids, the formation was affected.



Figure 3.3 – Drum Dryer

After drying to the desired solids level the webs were stored in fully sealed plastic bags and placed in the refrigerator.

Experiment Design

In total 12 cases were tested, in order to evaluate the effect of the basis weight and the different mechanical and chemical treatments. A base case or case 1 was designed to be used as a reference point relative to the other cases. For this case the pulp was refined

to 560 C.S.F. and no chemicals or fillers were added. In Table 3.1 is a summary of all the conditions evaluated.

Table 3.1 – Splitting Test Cases

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SOLIDS RANGE %	REFINING LEVEL (csf)	CHEMICAL DOSAGE (kg/Ton)				SPLITTING WEIGHT (g)
				Normal Clay	Modified Clay	C-Starch	C-PAM	
CASE 1: REF 560 csf; NO CHEMICALS - BASE CASE	101	46 TO 95	560	0	0	0	0	1100
	191	20 TO 96	560	0	0	0	0	1100
	277	41 TO 96	560	0	0	0	0	1100
	341	22 TO 96	560	0	0	0	0	1100
CASE 2: REF 740 csf; NO CHEMICALS	99	22 TO 95	740	0	0	0	0	250 TO 1100
	199	18 TO 95	740	0	0	0	0	250 TO 1100
	302	18 TO 92	740	0	0	0	0	250 TO 1100
	396	18 TO 95	740	0	0	0	0	250 TO 1100
CASE 3: REF 560 csf; ASH 17% (Normal Clay), NO C-STARCH	113	30 TO 95	560	280	0	0	0.1	1100
	202	29 TO 95	560	280	0	0	0.1	1100
	311	28 TO 93	560	280	0	0	0.1	1100
	400	30 TO 92	560	280	0	0	0.1	1100
CASE 4: REF 440 csf; NO CHEMICALS	300	36 TO 95	440	0	0	0	0.0	1100 & 1540
CASE 5: REF 560 csf; ASH 13% (NC), NO STARCH	314	39 TO 96	560	180	0	0	0.1	1100
CASE 6: REF 560 csf; ASH 22% (NC), NO STARCH	305	43 TO 95	560	370	0	0	0.1	1100
CASE 7: REF 560 csf; ASH 13% (MC), NO STARCH	317	40 TO 96	560	0	180	0	0.1	1100
CASE 8: REF 560 csf; ASH 18% (MC), NO STARCH	318	40 TO 95	560	0	280	0	0.1	1100
CASE 9: REF 560 csf; ASH 24% (MC), NO STARCH	318	38 TO 96	560	0	370	0	0.1	1100
CASE 10: REF 560 csf; C-STARCH = 15 kg/Ton, NO CLAY	303	39 TO 96	560	0	0	15	0.0	1100 & 1980
CASE 11: REF 560 csf; ASH 23% (NC), C-STARCH = 15 kg/Ton	346	42 TO 96	560	280	0	15	0.1	1100 & 1540
CASE 12: REF 560 csf; ASH 23% (NC), C-STARCH = 30 kg/Ton	341	44 TO 96	560	280	0	30	0.1	1100 & 1540

Splitting Energy Determination

For each one of the twelve cases shown in Table 3.1 the splitting apparatus energy loss was calculated. Once these values were obtained, the energy friction loss of the equipment was subtracted to find the splitting energy.

Cohesive and Bending Energy Determination

In order to obtain cohesive energy the bending energy must be subtracted from the splitting energy. Determination of the bending energy requires obtaining splitting energies over a range of basis weights. This was done for selected cases. It should be

noted that cohesive energy and splitting energy are related and that trends can be determined by examining only splitting energy.

During this part of the investigation four basis weights were chosen (100, 200, 300 and 400 g/m²), and for each basis weight different moisture content were also prepared as shown in Table 3.1 cases 1 to 3.

The principle behind the procedure that allows dividing the splitting energy into cohesive and bending energy is the fact that the cohesive energy is theoretically independent on the amount of fiber per unit area of the sheet (basis weight), while the bending energy depends on this factor. Considering this if the splitting energy versus basis weight curve is projected to zero basis weight for different solids content (Figure 3.4), the value of the cohesive energy can be found for each case and at the same time the bending energy can also be determined.

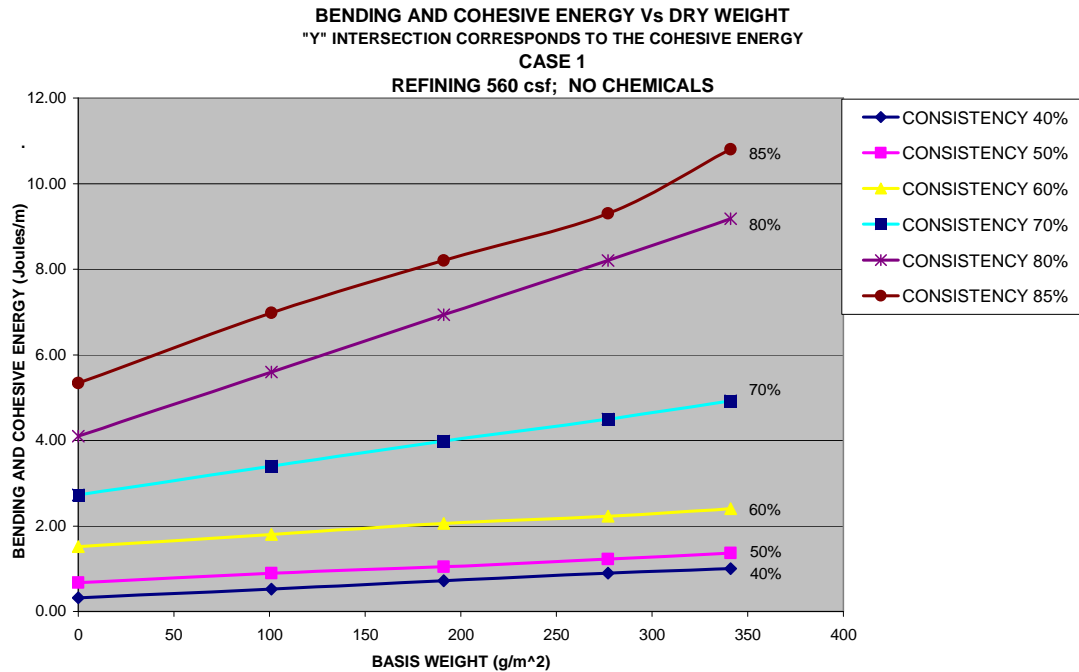


Figure 3.4 – Splitting Energy Vs Basis Weight Curve at Different Solids

Paper Splitting Apparatus

The energy required to split the paper comes from two suspended weights (splitting weights) that are linked at each part of a split previously made to the test specimens. As the weights fall down, the initial potential energy is transformed into:

1. Kinetic energy: Is related to the velocity the splitting weights acquire while the paper is being splitted
2. Splitting energy: Can be divided into the cohesive energy and the bending energy. While the cohesive energy does not depend on the basis weight, the bending energy does

3. Friction energy: The instrument is mechanically intensive, it has bands, pulleys, bearings and rolls. All of these elements, when in motion, consume energy which should not be considered when determining the paper splitting energy

During the experiments different splitting weights were used: 250, 460, 660, 1100 and 1540g (the weight for each side is half the total weight). The lowest weights were used to split the weakest paper. One of the experiments (case 2) consisted in splitting the same web with different splitting weights to identify if this could have an effect in the splitting energy. The rest of the experiments were performed using 1100g as the splitting weight. Although for the papers with high cohesive energy (case 10), splitting weight up to 1990g were required.

Apparatus Description

Figure 3.5 shows a schematic of the splitting apparatus and Figure 3.6 shows a picture of it.

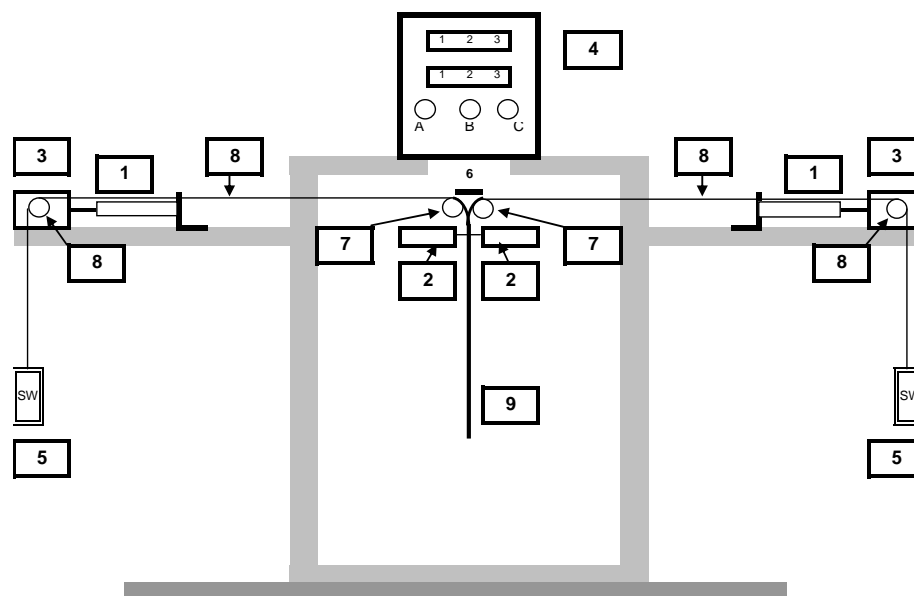


Figure 3.5 – Splitter Apparatus

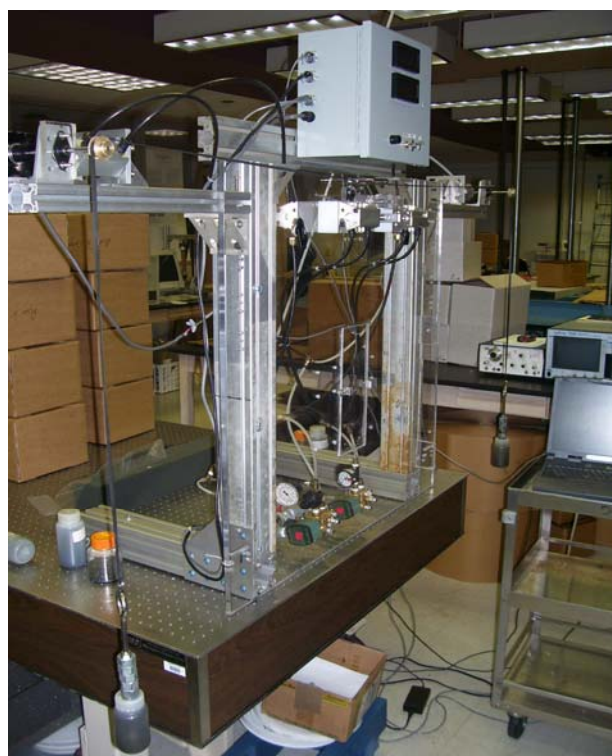


Figure 3.6 – Splitter Apparatus Picture

1. Pneumatic Brake Actuators: Allow the splitting weight to be released at the same time the paper is released. These are needed for wet webs so that the sheet does not support the splitting weights prior to the start of the test. The air pressure supplied to the pistons is controlled by pressure regulators. Enough pressure (around 30 Psi) is required to avoid the splitting weight movement but low enough to avoid damage in the shaft of the rotation sensor
2. Pneumatic Sheet Actuators: Holds the paper strip prior to the start of the test. The air pressure supplied to the pistons is controlled by pressure regulators. A low pressure (maximum 10 Psi) is required to avoid the paper strip damage
3. Rotation Sensors: Transmit a voltage (between 1 to 5 Volts) proportional to the velocity of the splitting weights. The information is sent to the display panel (4) and to the data acquisition system connected to the test apparatus. The velocity measurement is used to calculate the position of the splitting weights
4. Display Panel: Two LED displays used to displaying data from the two rotation sensors and for calibrating the sensors. The range should be the same for both sensors. The main power switch (A), run switch (B) and fuse (C) are located in this panel
5. Splitting weights: Used to split the paper. The difference between the potential energy and the kinetic energy of the weights, over the course of the test, correspond to the energy dissipated during the test. Energy is dissipated in three ways. (1) overcoming the cohesive energy of the sheet, (2) bending the sheet 90°, and (3) friction losses

6. Clamps Support: Used to attach the clips (that hold the paper during the splitting test) during the set up of the experiment
7. Wet Web Supporting Rolls: Once the clips hold each part of the initially split paper and if the wet web has solids below 30% the supporting rolls help to support the clips and avoid the paper rupture, due to the clip and band weights. When the test starts, the supporting rolls support the wet web (consistencies below 50%) and help to obtain a splitting angle of 90°. For higher consistencies the rolls are not used
8. Band and Geared Pulley: Links the paper strip with the splitting weight and transmit angular velocity to the sensor
9. Paper Test Sample: Paper strip is previously pre-split at one end and then inserted in the machine to perform the splitting test

Strip Samples Preparation

In each test case ten samples were prepared to be split in the apparatus. It is necessary to make a pre-split at one end of the strip, so the clips can be attached to that end of the strip. The split extends for approximately one inch of the total length of the strip. The pre-split was made using a razorblade to cut the strip in the plane of the paper as shown by the arrow in Figure 3.7. For wet webs this can be easily performed. For dry sheets it is necessary to wet the tip of the strip, in this condition the web expands in thickness and the cohesive energy of the sheet is reduced dramatically, allowing the procedure to be easily performed. Any excess of water was removed to avoid its propagation through the web. In this way two pieces of almost identical thickness can be obtained.



Figure 3.7 – Paper Cut at Half its Thickness

Apparatus Operation

Once the pre-split has been formed, the following procedure is used

1. Connect the computer used for data acquisition to the system
2. Connect power and air supplies to the equipment
3. Record the splitting weights, should be the same for both sides, and ideally the same for all the experiments
4. Turn on the main power switch on the control panel (D)
5. In the data acquisition program give a name to the test to be performed
6. Set to “On” the run switch, this releases the actuators and the pulleys

7. Place the belts that connect the splitting weights to the paper over the geared pulley that is on the rotation sensor shaft. Clip the bands clamp to the clamp support (Figure 3.8)
8. Insert the test sample with the wire side facing to the right and protruding from the pneumatic clamps long enough to be able to reach the top of each of the supporting rolls (Figure 3.8)
9. While holding the sample strip, turn the run switch to “Off”, be careful with your fingers. At this moment the sheet is held in position by the actuators (Figure 3.8)
10. Connect the clamps to the split tops of the test strip (Figure 3.8)
11. Adjust the band so enough tension is applied to the web, without breaking it
12. Set the data acquisition system to start recording when a high signal is seen on the run switch
13. Switch the run button to “On” to start the experiment and start recording data
14. When the test is complete, remove the pieces of paper from the clamps and return to step 5

In Figure 3.8 the following parts can be identified:

1. Clamp support
2. Clamps to hold the paper strip
3. Supporting rolls

4. Actuators to hold the paper strip
5. Paper strip

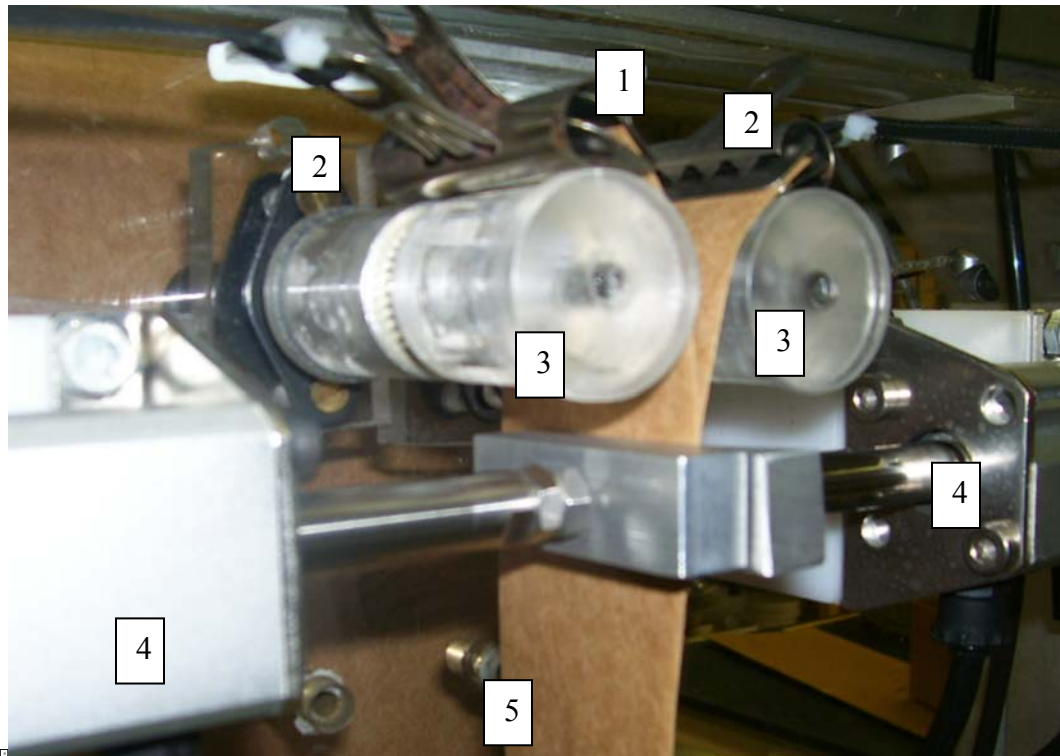


Figure 3.8 – Strip Ready to be Tested

Energy Calculations

The splitting apparatus is a device designed to measure the energy of two falling weights, which is composed of the potential energy and kinetic energy, which are joint to the ends of a split strip of paper. At the beginning of the test all the energy is in the form of potential energy, which depends on the splitting weight. Once the test starts, the initial

potential energy is transformed into kinetic energy and the energy consumed by the apparatus. During the test, the splitting weights start to fall and their velocity increases from 0 at the beginning to some value during the test. The kinetic energy can be calculated because the splitting weight velocity can be measured. The splitting weight velocity also allows calculation of the position of the weights during the experiment and then the potential energy associated with this position. The difference of these energies is the energy required to run the apparatus. This energy is composed of the friction energy associated with the mechanical devices and the energy required to split the web. Finally the energy required to split the web is also composed by the cohesive or internal energy of the paper and the energy required to bend the paper strip. All the energies are in the form of Joules per meter.

The equations that govern the apparatus operation are:

$$\text{Potential Energy}_{(\text{initial})} = \text{Potential Energy}_t + \text{Kinetic Energy}_t + \text{Apparatus Energy Loss}_t \quad 3.1$$

$$\text{Apparatus Energy Loss} = \text{Friction Energy} + \text{Splitting Energy} \quad 3.2$$

$$\text{Splitting Energy} = \text{Cohesive Energy} + \text{Bending Energy} \quad 3.3$$

Equation 3.1 can be restated as

$$mgh_i = mgh_t + (\frac{1}{2})mV_t^2 + \text{Apparatus Energy Loss}_t \quad 3.4$$

Where: h_i = initial height of the splitting weights, [m]

h_t = height at time t, [m]

m = total splitting weight, [kg]

$$V_t = \text{mean velocity of the splitting weights at time } t, [\text{m/s}]$$

Taking h_i to be the origin of the system, the equation 3.4 can be written as

$$\text{Apparatus Energy Loss} = -mgh_t - (\frac{1}{2})mV_t^2 \quad 3.5$$

Considering that h_t will always be negative, the equation can finally be written as

$$\text{Apparatus Energy Loss} = m(gh_t - (\frac{1}{2})V_t^2) \quad 3.6$$

Apparatus Mechanical Losses

The splitting apparatus has several mechanical components which consume energy during the test procedure. Two main systems can be identified, the rotational sensor system, items 3 and 8 in Figure 3.5, and the supporting rolls, item 7 in Figure 3.5. Several components interact during this process. The band that links the splitting weight with the splitting paper and moves over the geared pulley. The geared pulley is mounted in a shaft that transmits the angular velocity to the rotation sensor. This shaft is supported between two sets of bearings and connected to the rotation sensor through a coupling. In Figure 3.9 the following parts can be identified.

1. Rotation sensor
2. Flexible coupling
3. Pulley shaft
4. Geared pulley
5. Band

6. Actuator

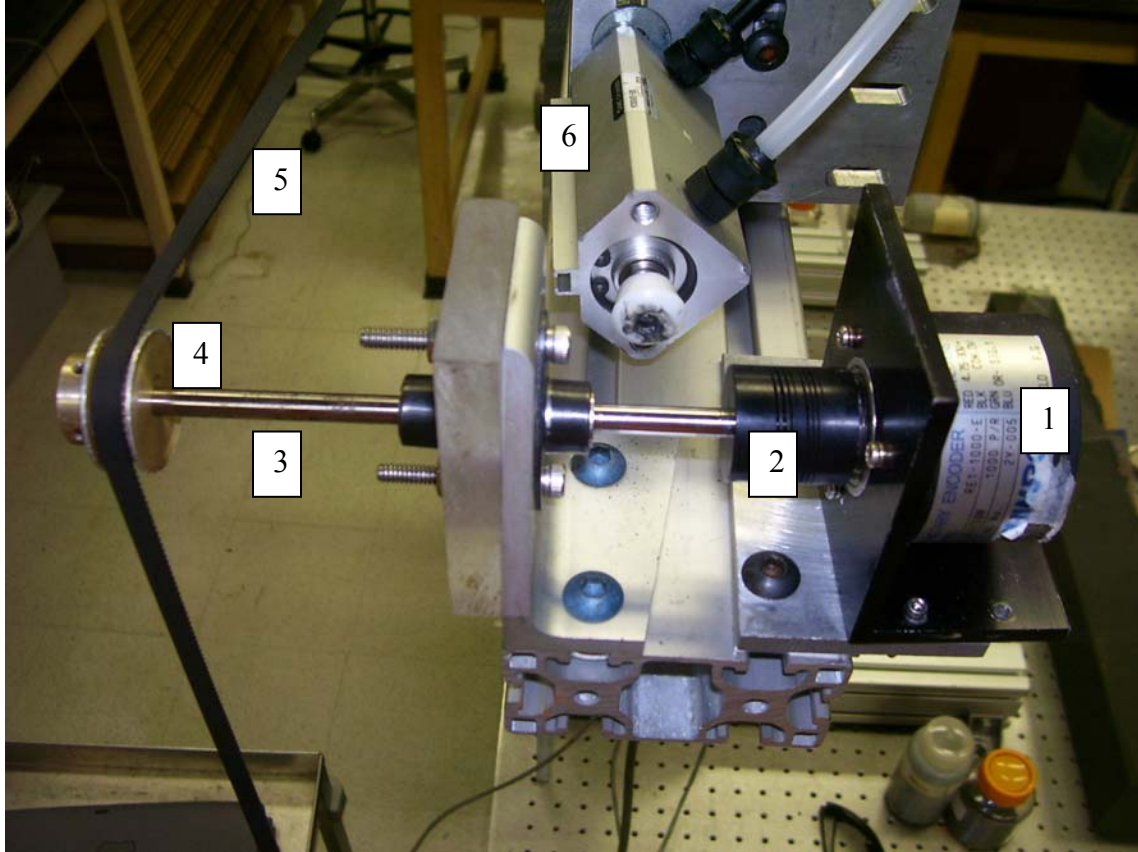


Figure 3.9 – Angular Velocity Transmission System

The supporting rolls are only used when the web solids are below 50%. At solids content above 50% the strip does not touch the supporting rolls and there is no energy loss due to this aspect.

A simple test was performed to quantify the mechanical losses of the apparatus. The same test was performed independently for each side. The configuration for the test

is shown in Figure 3.10 and 3.11. A counter weight was used in place of the paper. In place of the splitting weight a series of masses (125, 233, 330, 550 and 770g) were used. As with the paper splitting test the velocity measurements from the pulleys were used to calculate the difference between the potential and kinetic energies of the weights. It was assumed that the plastic strip offered negligible resistance to bending. Therefore, since there is no cohesive force to overcome, the energy difference is equivalent to the frictional losses.

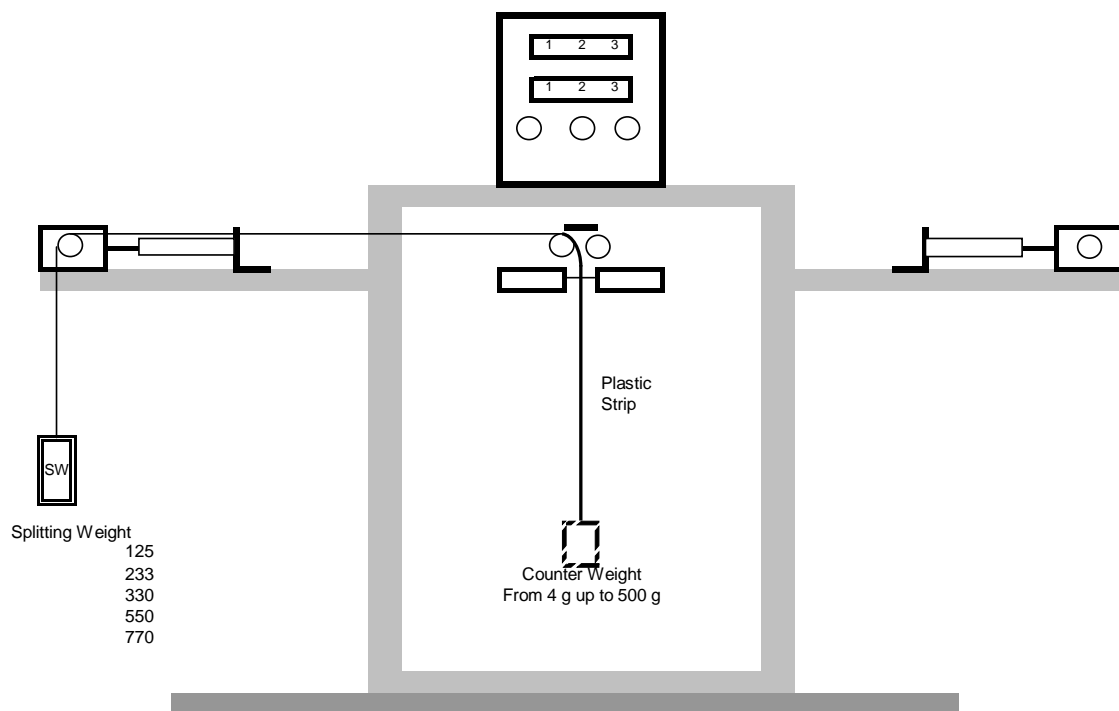


Figure 3.10 – Friction Experiment



Figure 3.11 – Friction Plastic Strip Experiment Picture

The frictional losses for the cases run are shown in Figure 3.12. The curves for the data were projected back to frictional losses corresponding to a counter weight of zero mass. It is assumed that this is the frictional loss for the splitting apparatus when the supporting rolls are not being used (solids above 50%).

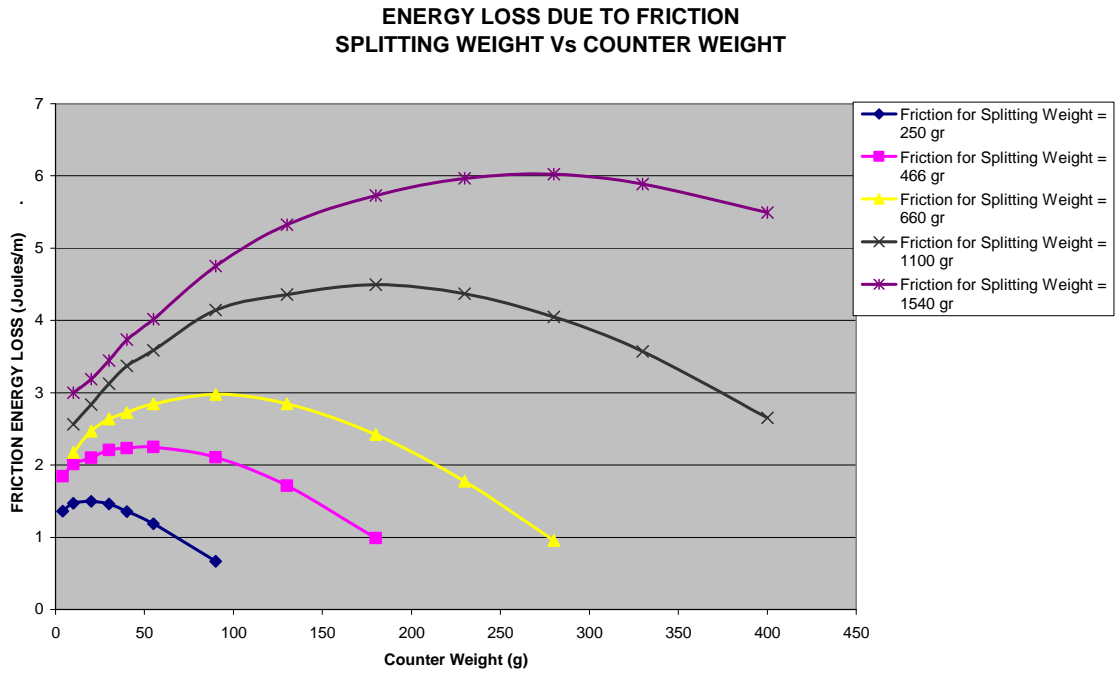


Figure 3.12 – Friction Determination: Splitting Weight Vs Counter Weight

Table 3.2 – Experiments for Friction Determination

SPLITTING WEIGHT (g)	Counter Weight (g)												
	4	10	20	30	40	55	90	130	180	230	280	330	400
125	8	8	8	8	8	8	8	8	8	8	8	8	8
233	8	8	8	8	8	8	8	8	8	8	8	8	8
330		8	8	8	8	8	8	8	8	8	8	8	8
550		8	8	8	8	8	8	8	8	8	8	8	8
770		8	8	8	8	8	8	8	8	8	8	8	8

To find the friction energy loss including the effect of the supporting rolls, the apparatus energy loss obtained for the wet webs of case 2 (unrefined paper) was compared with the energy loss obtained from the friction test when using counter weights equivalent to the wet paper weight. During case 2 the cohesive energy of the paper must be low because the fiber has not received the mechanical treatment required to develop

the strength properties. Additionally the solids content of the web (18%) is low enough that the energy required for bending purposes can be disregarded. Based on these assumptions, the apparatus energy loss in this situation can be assumed to be the result of the friction energy of the system and the energy required to raise the wet web. The apparatus energy loss from both experiment were very similar. A detailed explanation of this method is presented in Chapter 4.

Instron Testing

The Instron tester was used to complement the information obtained with the splitter apparatus. Test specimens of one inch wide by eight inches long were prepared to be tested. At least four tests were performed for each one of the webs prepared in the Dynamique equipment. The equipment gives the stress-strain curve, and values for the % of strain at maximum load, the maximum load, the tensile energy absorption and modulus of elasticity.

CHAPTER 4

RESULTS AND DISCUSSION

Introduction

The two primary pieces of experimental equipment used in this study were the splitter apparatus and the Instron tester. Experiments were designed in order to obtain the friction energy loss of the splitter apparatus, the variation of the web splitting energy with solids content when different mechanical and chemical treatments are used, the cohesive and bending energy variation with the web solids content and the usual tensile and strain properties obtained from the Instron instrument.

In section two of this chapter the testing and analysis methodology is presented. The procedure used to obtain the apparatus energy loss versus distance graphs (the basis for all results obtained from the apparatus) is explained as well as the most important considerations taken into account in analyzing the results. The data is presented for all the cases evaluated with the splitter apparatus and the Instron tester. Finally an explanation on how the information obtained from the apparatus energy loss graph can be used to make the splitting energy versus solids graph for the different cases is discussed.

In the third part of this chapter the details of the method used to calculate the apparatus friction energy loss is presented. The apparatus was divided in the left and right sides and for each side two main sources of friction were identified, the loss due to the angular velocity transmission and the loss due to the supporting rolls. This loss was subtracted from the apparatus energy loss to obtain the splitting energy of the paper.

The method used to determine the splitting energy for all the cases is presented in section four. The effect of the different mechanical and chemical treatments on the splitting energy with the solids variation is also presented. The results are compared against a base case.

Section five presents the results for splitting energy calculated with the apparatus. This energy is composed of the cohesive energy and the bending energy of the paper. The method used to find the cohesive and bending energy variation against the solids is also presented along with the results obtained for selected cases.

To support the data obtained with the splitter tester standard tensile tests were performed on paper samples from all the cases studied. The tensile test provides tensile strength and strain at maximum load, the information related to this test is presented in section six.

Finally section seven compares the results from the splitter apparatus and Instron instrument, graphs of the cohesive strength index and the tensile strength index are provided for selected cases. According to the Page equation for wet web tensile strength there should be a linear relation between both indices. As an additional source to validate the splitter apparatus results, the Osterberg equations developed to model the web behavior when pulled from a solid surface were used. The apparatus offers data for all the variables required on the equation except strain, so the equations were solved for the strain and its value was compared to that obtained from the Instron tests.

Testing and Analysis Methodology

The splitting apparatus allows the determination of the energy (Joules) required to split a strip of paper under a wide range of conditions. This information is obtained by recording the time, the velocity of the crack propagation (velocity of falling splitting weight) and calculating the distance traveled by the splitting weights which corresponds to the crack propagation distance through the strip. With this information the behavior of the splitting paper can be described in terms of the energy expended in splitting the sheet.

The base graph produced in the experiments is the apparatus energy loss versus distance graph, presented in Figure 4.1.

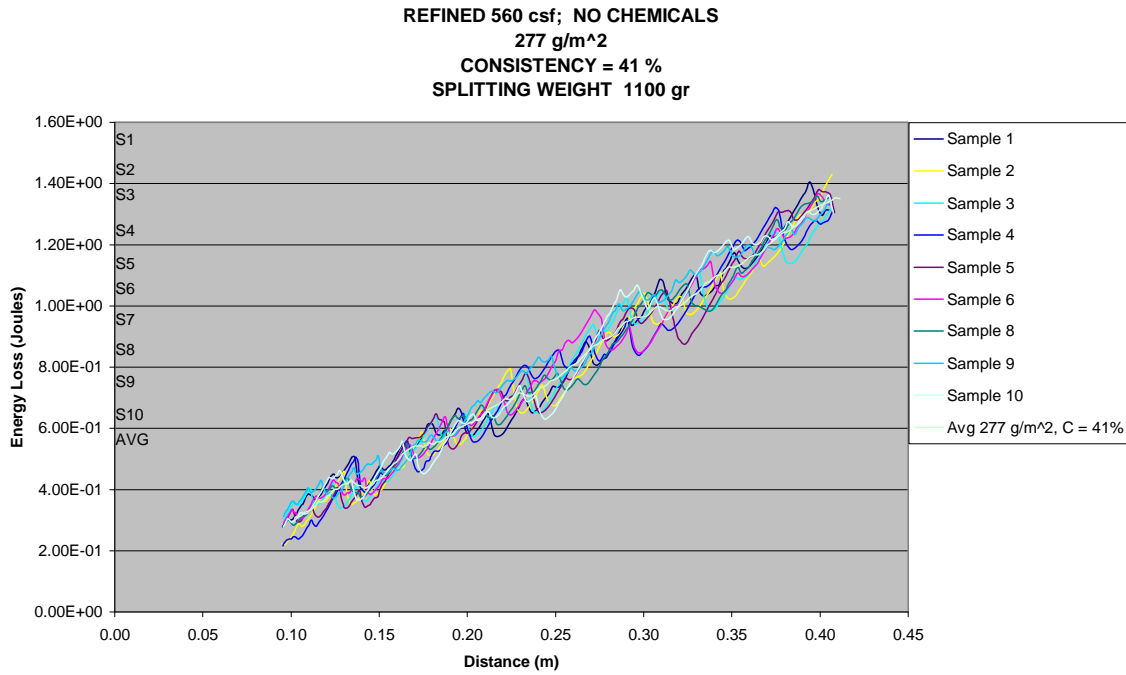


Figure 4.1 – Apparatus Energy Loss Vs Distance

In this particular case the graph represents the results of a splitting test done to a web with a refining level of 560 C.S.F., with no chemical or filler additives, with a basis weight of 277 g/m², a solids content of 41% and using splitting weights of 1100g. In this case nine strips were evaluated. As can be clearly seen, the energy loss is linearly dependent on the distance traveled by the splitting crack.

The two main sources of energy consumption are the friction loss and the energy required to split the paper. The effect of the splitting weights, the angular velocity transmission system and the supporting rolls, the elements contributing to friction, do not change during the test so the friction will be the same. Additionally a well formed web will have the same properties at all points along the strip, so no change in splitting energy should occur.

It is important to emphasize that the splitting weights should offer the system enough energy to overcome the energy consumed by friction and by splitting. If there is not enough energy stored, the splitting process will start (in some cases with too low energy the process can not start) but the velocity of the crack propagation will go down until the process stops. In this case the results obtained are not reliable.

Another important factor to consider is the low strength of strips with low solids content (below 20%). When the web is too weak it can not support the tension applied when the samples are clamped to the splitting weights, even though the tension is low due to the action of the pneumatic break actuators (element 1 in Figure 3.5). In some cases the weight of the clamp is enough to break the strip.

During the splitting test, to eliminate any external noise that could affect the results associated with the initial and final part of the procedure, only the data that were produced between distances of 0.1 m to 0.4 m were recorded. The system can collect data from a distance corresponding to 0.0 m and up to the strip longitude that was around 0.5 m. Disregarding the first and last 0.1 m gives confidence that the data collected corresponds to the time when the paper was being split.

Since there is a linear dependence between the energy losses during the experiment, and the crack propagation distance, a linear trend line was fit to the data obtained from each sample. The slope of the trend lines represents the apparatus energy loss per unit distance in Joules per meter. Figure 4.2 shows the results for the data shown in Figure 4.1. Table 4.1 presents the equations for the trend lines and the corresponding R^2 values.

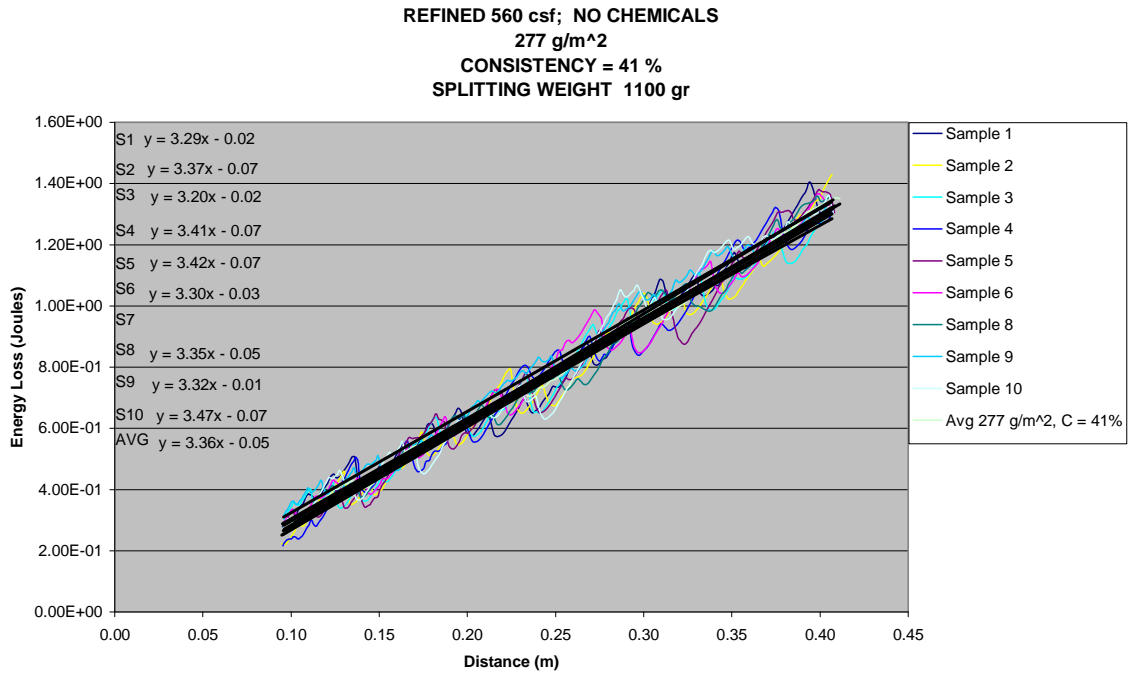


Figure 4.2 – Tendency Lines of Apparatus Energy Loss Vs Distance

Table 4.1 – Linear Trend Equations and R^2

SAMPLE	TREND EQUATION	Slope	R2
1	3.29 X	3.29	0.97
2	3.37 X	3.37	0.98
3	3.20 X	3.20	0.98
4	3.41 X	3.41	0.98
5	3.42 X	3.42	0.97
6	3.30 X	3.30	0.98
8	3.35 X	3.35	0.98
9	3.32 X	3.32	0.99
10	3.47 X	3.47	0.97
	Average	3.35	
	Standard Deviation	0.08	

In Table 4.1 it can be seen that the slope dispersion is low which allows us to conclude that the reproducibility of the test is high. The mean value is 3.35 J/m, the highest value is 3.47 J/m and the lowest value is 3.20 J/m, the standard deviation is 0.08.

The same procedure was applied to all the cases shown in Table 4.2. It is to be noted that the base case or case 1, serves as the comparison case for the rest of the results. This case was made with pulp refined to 560 C.S.F. and with no chemicals or filler addition. With the data obtained from cases 1, 2 and 3 it was possible to determine the cohesive and bending energy, with the rest of the cases only the splitting energy was obtained. In Table 4.3 are the results for the apparatus energy loss mean value and standard deviation for case 1. The apparatus energy loss versus distance graphs for cases 1 to 3 are presented in Appendix A.1. The apparatus energy loss versus distance graphs for cases 4 to 12 are presented in Appendix B.1. The mean and standard deviation for the apparatus energy loss as well as the friction energy loss and the splitting energy are provided in Appendix C for all the cases.

Almost all the experiments were performed using a total splitting weight of 1100g. One exception was the tests performed to the unrefined pulp (case 2) that helped to determine the friction energy loss of the instrument for wet webs, during this conditions several splitting weights between 250 and 1100g were used. The other exception was when performing the experiment for the higher solids content webs (above 85%) in the cases were the pulp was highly refined and when starch was added to the furnish. In these cases 1100g of splitting weight could not split the paper, so the splitting weight was increased to 1540g and even to 1980g for the case when the starch was the only chemical added, this case corresponds to the strongest web made.

In the table the abbreviation NC correspond to the use of normal or uncoated clay while MC corresponds to starch modified clay.

Table 4.2 – Splitting Test Conditions Cases 1 to 12

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SOLIDS RANGE %	REFINING LEVEL (csf)	CHEMICAL DOSAGE (kg/Ton)				SPLITTING WEIGHT (g)
				Normal Clay	Modified Clay	C-Starch	C-PAM	
CASE 1: REF 560 csf; NO CHEMICALS - BASE CASE	101	46 TO 95	560	0	0	0	0	1100
	191	20 TO 96	560	0	0	0	0	1100
	277	41 TO 96	560	0	0	0	0	1100
	341	22 TO 96	560	0	0	0	0	1100
CASE 2: REF 740 csf; NO CHEMICALS	99	22 TO 95	740	0	0	0	0	250 TO 1100
	199	18 TO 95	740	0	0	0	0	250 TO 1100
	302	18 TO 92	740	0	0	0	0	250 TO 1100
	396	18 TO 95	740	0	0	0	0	250 TO 1100
CASE 3: REF 560 csf; ASH 17% (Normal Clay), NO C-STARCH	113	30 TO 95	560	280	0	0	0.1	1100
	202	29 TO 95	560	280	0	0	0.1	1100
	311	28 TO 93	560	280	0	0	0.1	1100
	400	30 TO 92	560	280	0	0	0.1	1100
CASE 4: REF 440 csf; NO CHEMICALS	300	36 TO 95	440	0	0	0	0.0	1100 & 1540
CASE 5: REF 560 csf; ASH 13% (NC), NO STARCH	314	39 TO 96	560	180	0	0	0.1	1100
CASE 6: REF 560 csf; ASH 22% (NC), NO STARCH	305	43 TO 95	560	370	0	0	0.1	1100
CASE 7: REF 560 csf; ASH 13% (MC), NO STARCH	317	40 TO 96	560	0	180	0	0.1	1100
CASE 8: REF 560 csf; ASH 18% (MC), NO STARCH	318	40 TO 95	560	0	280	0	0.1	1100
CASE 9: REF 560 csf; ASH 24% (MC), NO STARCH	318	38 TO 96	560	0	370	0	0.1	1100
CASE 10: REF 560 csf; C-STARCH = 15 kg/Ton, NO CLAY	303	39 TO 96	560	0	0	15	0.0	1100 & 1980
CASE 11: REF 560 csf; ASH 23% (NC), C-STARCH = 15 kg/Ton	346	42 TO 96	560	280	0	15	0.1	1100 & 1540
CASE 12: REF 560 csf; ASH 23% (NC), C-STARCH = 30 kg/Ton	341	44 TO 96	560	280	0	30	0.1	1100 & 1540

Table 4.3 – Apparatus Energy Loss for Case 1

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)	
				APPARATUS LOSS	Std Dev
CASE 1: REF 560 csf; NO CHEMICALS	101	1100	46	3.11	0.09
		1100	63	4.55	0.12
		1100	78	7.47	0.21
		1100	86	9.39	0.16
		1100	95	7.75	0.19
CASE 1: REF 560 csf; NO CHEMICALS	191	1100	20	2.90	0.09
		1100	41	3.19	0.09
		1100	56	3.87	0.06
		1100	71	6.58	0.10
		1100	78	8.58	0.20
CASE 1: REF 560 csf; NO CHEMICALS	277	1100	41	3.35	0.08
		1100	57	4.12	0.11
		1100	72	7.47	0.24
		1100	79	10.09	0.19
		1100	96	10.39	0.28
CASE 1: REF 560 csf; NO CHEMICALS	341	1100	22	3.32	0.12
		1100	43	3.52	0.04
		1100	57	4.34	0.15
		1100	68	6.65	0.17
		1540	85	13.49	0.19
		1540	96	12.65	0.45

Friction Calculation

To calculate the splitting energy it was necessary to find the apparatus energy loss required to move the equipment, or friction energy. To calculate the friction loss the apparatus was divided into the left and right sides and each side was consider separately. Each side is composed of two main systems responsible for the energy loss, the angular velocity transmission system (elements 3 and 8 in Figure 3.5) and the roll support system (element 7 in Figure 3.5). Considering the apparatus design and the test to be performed in it, it can be concluded that for the test conditions the friction energy loss of the velocity transmission system mainly depends on the splitting weight, while the friction energy loss for the roll support system also depends on the counter weight (shown in Figure 3.10).

The first task was to measure the total friction loss in the left and right side in an independent way to be sure that the energy loss in both sides was the same. This was performed simulating the paper splitting test by replacing the strip of paper by a thin flexible plastic strip (as seen in Figure 3.11) and eliminating the splitting process. The splitting process can be eliminated because the plastic strip is not split during the experiment and also because the caliper of the strip was low enough to avoid any energy required to bend it. In total 400 tests were performed, 200 for each side, and with different splitting weight-counter weight configurations. From the data obtained graphs like the one in Figure 4.3 were created. This graph represents the situation when performing the test with 550g of splitting weight independently in each side and using a counter weight of 55g. In the graph only the average friction energy loss (of four results per side) of the left and right sides are presented. As can be seen the friction energy loss is quite similar for both sides. The total energy loss of the system is the sum of the loss on each side. The friction energy loss is also linear as expected because there is no external force that could affect the operation of any of the two systems once the test starts. A trend line was created to determine the friction energy loss per distance, as shown in Figure 4.4. The procedure was repeated with different splitting weight-counter weight configurations and the average results shown in Table 4.4 were obtained. In Appendix D.1 are all the graphs corresponding to the data shown in Table 4.4.

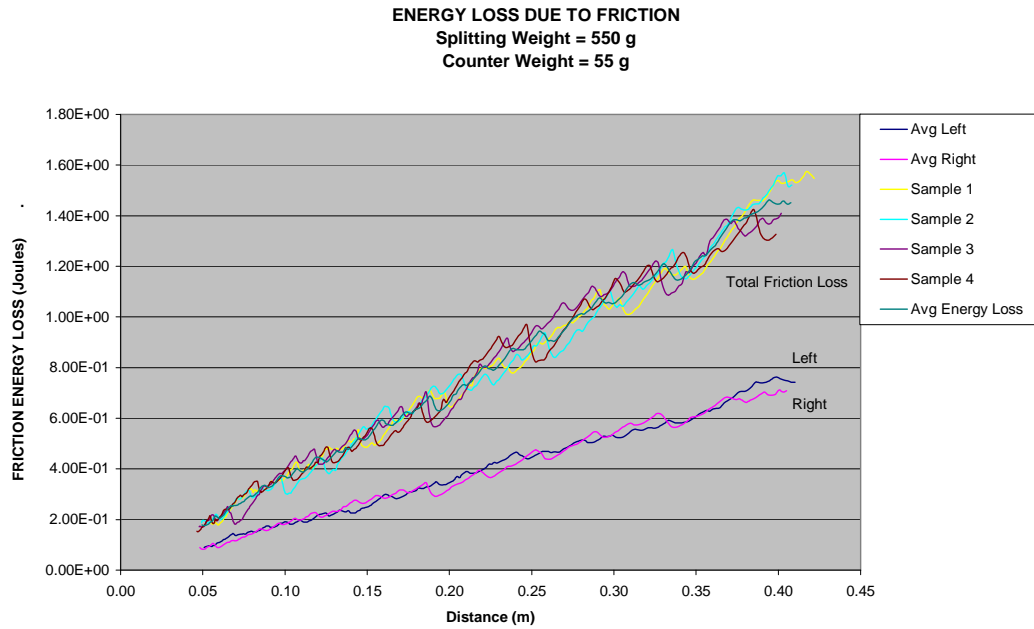


Figure 4.3 – Friction Energy Loss Curves (Left, Right Side and Total)

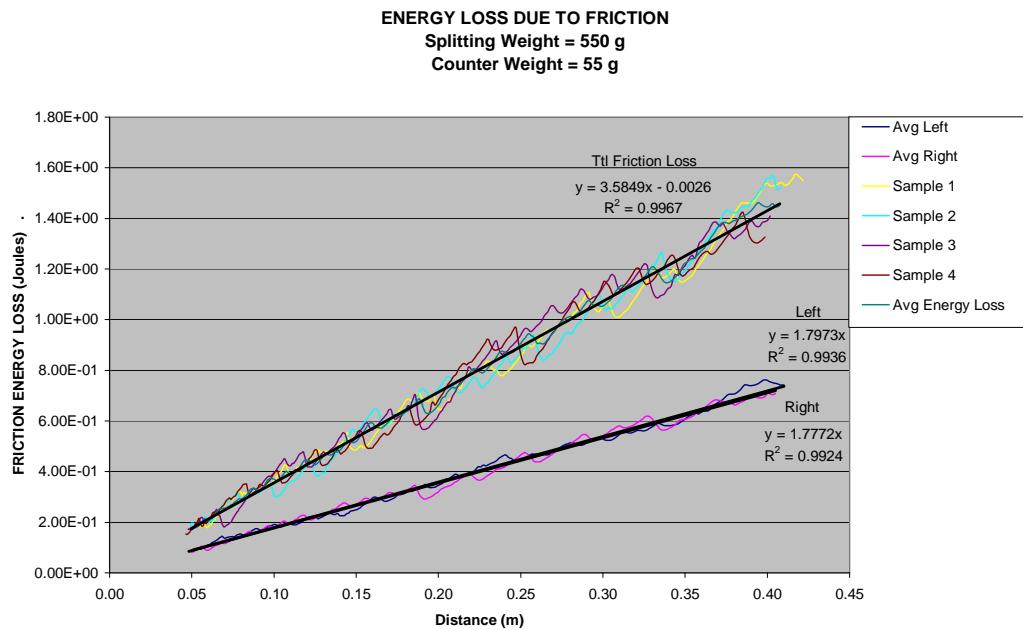


Figure 4.4 – Tendency Lines of Friction Energy Loss Vs Distance

Table 4.4 – Friction Energy Loss Calculation

SPLITTING WEIGHT PER SIDE (g)	COUNTER WEIGHT (g)												
	4	10	20	30	40	55	90	130	180	230	280	330	400
125	1.36	1.47	1.49	1.46	1.36	1.19	0.67						
233	1.84	2.01	2.10	2.20	2.23	2.25	2.10	1.71	0.99				
330		2.18	2.47	2.64	2.72	2.85	2.98	2.84	2.42	1.78	0.95		
550		2.56	2.84	3.12	3.37	3.58	4.15	4.36	4.50	4.37	4.05	3.57	2.65
770		3.00	3.19	3.45	3.74	4.02	4.75	5.33	5.73	5.96	6.02	5.89	5.49

With these results a graph like the one in Figure 3.12 was obtained. In this graph it can be seen how the friction energy loss changes with the splitting weight and the counter weight. The friction energy loss when the counter weight is zero grams, corresponds to the case where the only factor responsible of the friction loss is the angular velocity transmission system. The value of friction for counter weight zero was found by fitting trend lines as shown in Figure 4.5. It was found that when the splitting weight is 250g the loss is 1.31 J/m, for 466g the loss is 1.82 J/m, for 660g the loss is 2.05 J/m, for 1100g the loss is 2.36 J/m and when the splitting weight is 1540 the friction energy loss is 2.67 J/m. Using this data the graph shown in Figure 4.6 was created. The data for the splitting weight of 1980g was extrapolated, by assuming a linear trend for the previous three data points.

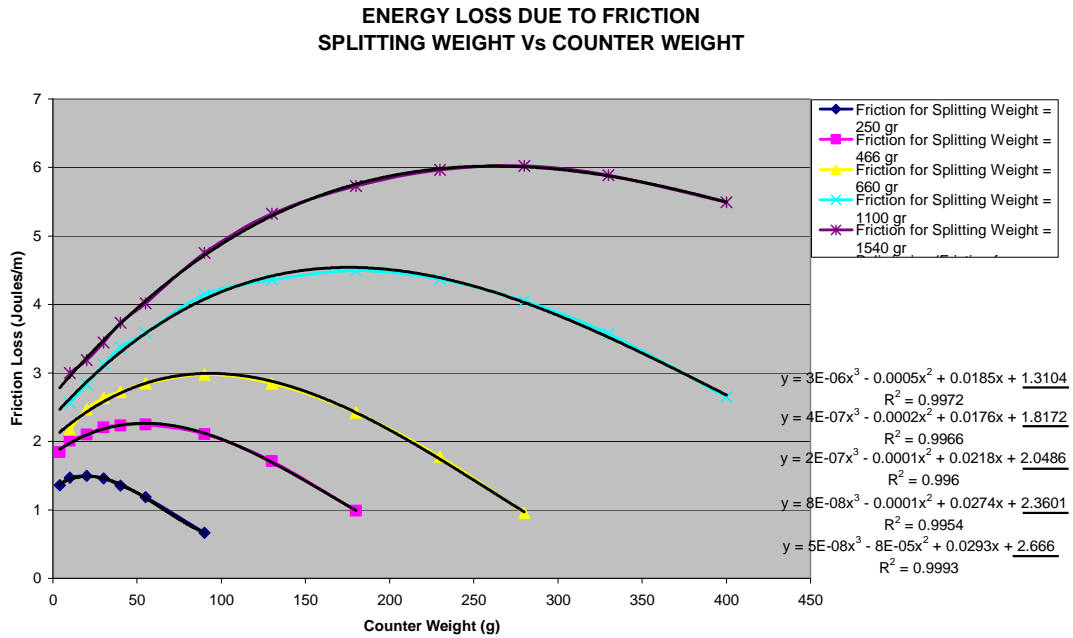


Figure 4.5 – Tendency Lines for Friction Energy Loss

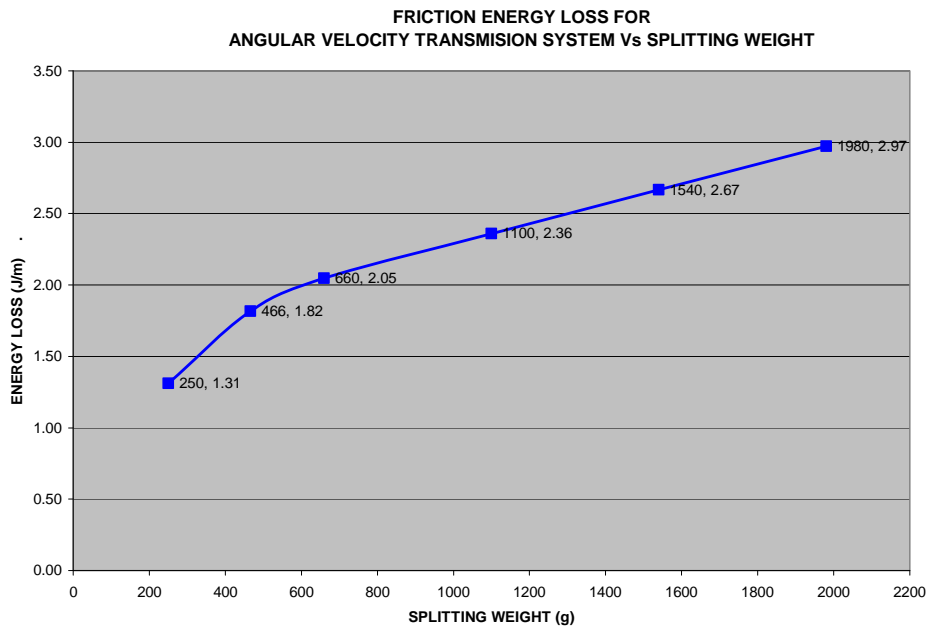


Figure 4.6 – Friction Energy Loss for Angular Velocity Transmission System

As previously discussed, the friction energy loss at the zero counter weight condition represents the energy loss when splitting strips with solids content higher than 50%. At such solids the internal energy of the web is high enough to avoid the contact between the strip and the supporting rolls while the strips are being split and the only source of energy loss due to friction is the velocity transmission system. When splitting webs with lower solids the strip touches the supporting rolls adding losses to the system. To be able to determine the energy friction loss for these conditions, webs with low mechanical treatment (740 C.S.F.), at low solids content (18 to 25%) and corresponding to different basis weights were evaluated in the splitter tester using different splitting weights. As with a normal splitting test, the apparatus energy loss measured is equal to the sum of the splitting energy (cohesive plus bending energy) and the friction energy loss. A wet web with solids content between 18 and 25% and produced from pulp with low refining level will show a cohesive and a bending energy that was assumed to be negligible when compared with the friction energy loss of the system. Therefore, the apparatus energy loss when splitting these strips will be considered to be the friction energy loss of the supporting rolls and the velocity transmission system together. The results obtained during the experiments does not show any major difference in the apparatus energy loss when considering different basis weights, so it can be concluded that for this solids content range the effect of basis weight on the bending energy is negligible.

When the solids start to increase the wet paper starts to weigh less and the cohesive energy of the fiber starts to increase, under these conditions the friction induced by the paper strip to the supporting rolls will decrease. This situation will continue until testing webs with solids higher than 50% when the paper strip does not touch the supporting rolls and the friction energy loss is only the one due to the velocity transmission system. To consider the reduction in the friction loss due to this effect an intermediate friction energy loss was created based on the observations made during the experimentation process. At the end and depending on the web solids three different friction levels were considered. Friction level 1 for webs with solids between 18 and 37%, level 2 for web with solids between 38 and 50% and level 3 for solids higher than 50%. Figure 4.7 shows how depending on the splitting weight and on the solids content the friction of the apparatus can be determined.

To prove the assumption of the low bending and cohesive energy for high wet unrefined webs, the apparatus energy loss results obtained under these conditions were compared with the results obtained from the friction test performed on the plastic strip when the counter weight was equal to the paper strip weight. As previously stated when performing the test with the plastic strip, the splitting energy can be considered as zero and the apparatus energy loss will depend on the friction loss due to the velocity transmission and the supporting roll systems. Both systems losses depend on the splitting energy and the counter weight. The results for both experiments are shown in Table 4.5.

In the table all the results for the plastic strip friction test experiments are close but higher than the results for the apparatus energy loss performed on the wet unrefined web. Under these conditions it is reasonable to consider the apparatus energy loss when splitting low refined, low solids webs as the friction energy loss for the system when performing tests with low solids content sheets. This friction energy loss will be the same for all the strips regardless of the mechanical or chemical treatment performed to the pulp and depending only in the solids content of the web.

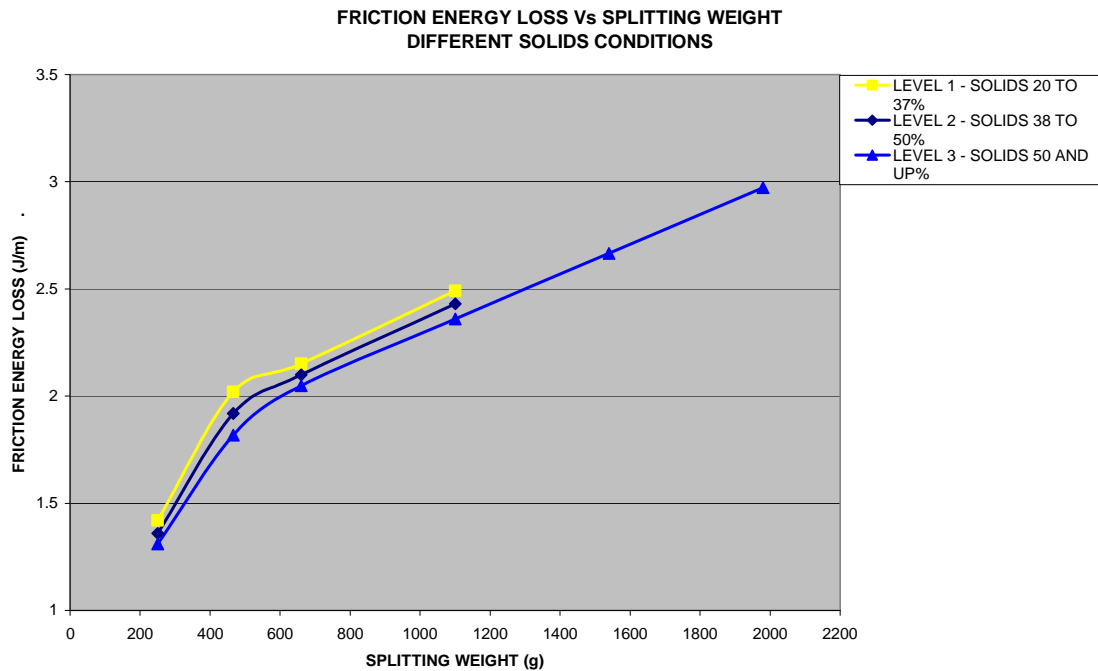


Figure 4.7 – Friction Energy Loss Levels

Table 4.5 – Apparatus Energy Loss Vs Friction Loss

SPLITTING WEIGHT (g)	APPARATUS ENERGY LOSS (J/m)	FRICTION TEST ENERGY LOSS (J/m)
250	1.46	1.47
466	2.14	2.21
660	2.35	2.59
1100	2.56	2.85

Splitting Energy

Once the friction energy is subtracted from the total apparatus energy loss the splitting energy is obtained which represents the energy required to split a strip of paper using this equipment. This splitting energy is composed of the cohesive energy or the energy required to keep the fibers together and of the bending energy, which is the energy required to bend the strip (90°) when performing the test. The graph of the splitting energy versus consistency is presented in Figure 4.8 for the base case or case 1.

The graph shown in Figure 4.8 was obtained by connecting the seven data shown by the markers with a smoothed line. The same procedure was used to connect the data from the different cases. In the Figure 4.8 five phases can be distinguished. Phase 1 starts at solids of 10% and goes up to 20% solids, this phase was not measured in this study. Phase 2 starts at 20% and goes up to 50%, in this zone the splitting energy slowly increases due to the effect of the surface tension that after reaching its maximum effect slowly goes down, at the same time some inter fiber bonds starts to form. Phase 3 starts at 50% and goes up to 80%, in this zone the splitting energy goes exponentially up and is the result of the inter fiber hydrogen bonding formation. Then comes phase 4, where the splitting energy still goes up but at a slower rate and eventually reaches a maximum value at around 88%, this could be explained by the stiffness of the fibers due to the low moisture content. The final zone goes from 88 to 96% in this region the splitting energy goes down returning to the same values the web had when the solid were around 80%. The responsible of this behavior is not completely understood and additional tests are required. Although the solids values to separate the phases presented here are not the same for all the webs they are very close for all the different cases. This shape is similar to the one presented in Figure 2.3 created by Brecht and Erfurth (7) for tensile test and also is similar to the curve created by Robertson and presented in Figure 2.4.

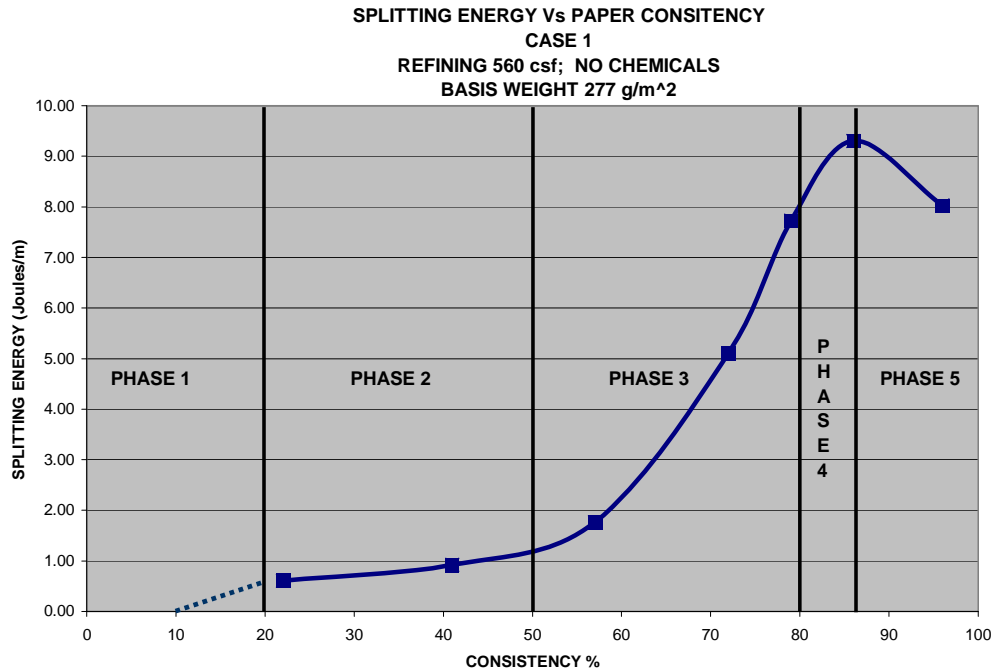


Figure 4.8 – Splitting Energy Vs Consistency

In total, 120 different webs conditions were evaluated and 1200 tests were performed in the splitter apparatus. The conditions represents different mechanical and chemical treatments as well as different basis weights, all the conditions performed at different solids contents as shown in Table 4.2. The test was designed to determine how the splitting energy versus solids graph change with the web basis weight, refining level, clay addition, and starch modified clay addition. Also some tests to evaluate the effect of the cationic corn starch over sheets with different clay content but similar ash content were performed.

Basis Weight Effect

For cases 1 to 3 different basis weights were considered. A graph presenting the results for the base case can be seen in Figure 4.9. It is clear how the increase in the fiber amount used to prepare the sheet increases the splitting energy. As basis weight increases it should be expected that the energy required to bend the sheet will also increase. This increase will be used to separate the cohesive and bending energy and will be discussed in a next section. For the base case there was no measurement made for a web with 300 g/m², to find this curve data were interpolated between the results obtained for the 277 and 341 g/m² curves. This was done in order to make direct comparisons with other cases.

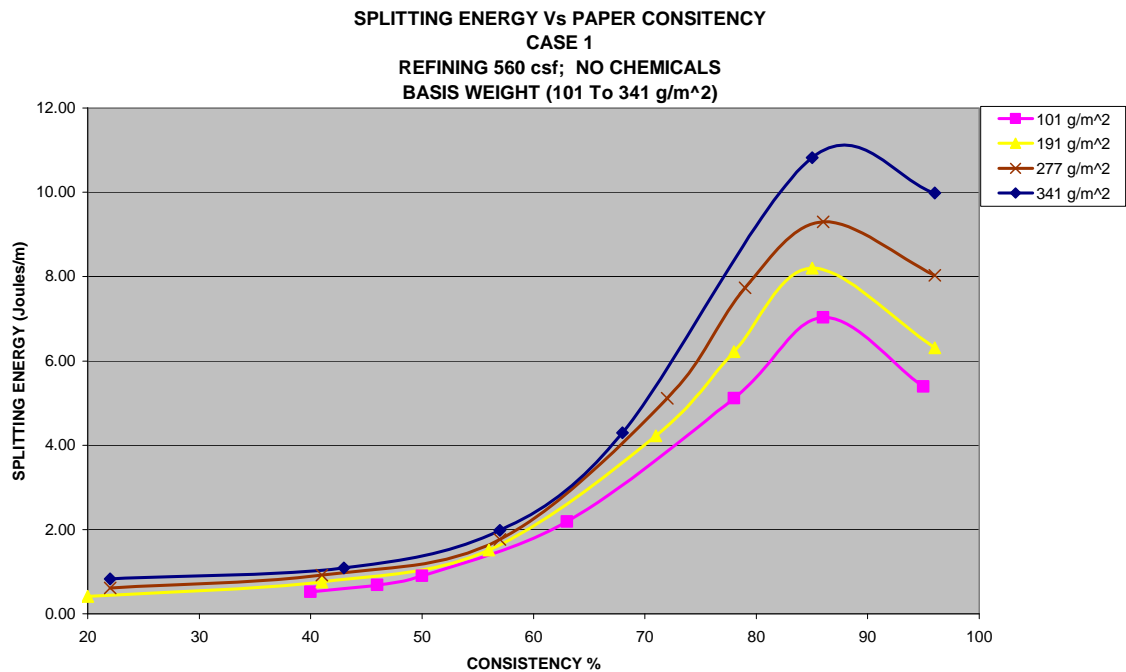


Figure 4.9 – Splitting Energy Vs Consistency for Different Basis Weights – Base Case

Mechanical Treatment

Figure 4.10 shows the splitting energy variation with three levels of mechanical treatment corresponding to 440, 560 and 740 C.S.F. The basis weight for all runs was 300 g/m². Considering a refining level of 740 C.S.F. as a very low one, it is clear how the refining increases the energy through the entire solids range. It is also clear how the increase of the refining level from 560 to 440 C.S.F. does not represent any additional effect. A low mechanical treatment will not significantly increase the surface area of the fiber nor its flexibility, both are main requirements to improve the fibers bonding ability.

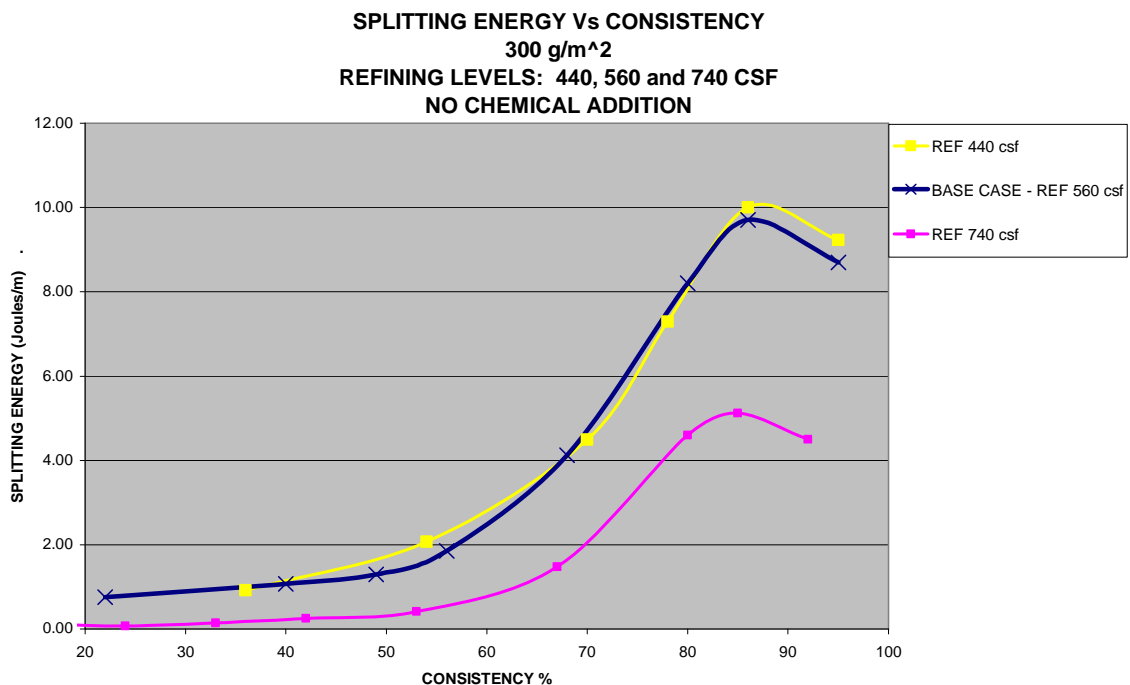


Figure 4.10 – Splitting Energy Vs Mechanical Treatment

Normal Clay Addition

Figure 4.11 shows the splitting energy variation with three levels of clay addition obtaining 13, 17 and 22% of ash content on the web. The basis weight was around 310 g/m² (3% higher than the base case weight). For the entire solids range, the splitting energy is lower for the webs with high ash content. It also can be noted that for the cases of 13 and 17% ash, there is no significant difference, but once the ash is increased even more to 22% the energy reduces in an appreciable way. This implies that a critical ash content must be above 17% and below 22% ash content which affects the strength of the web. Similar critical points may be found in the range between 0 and 13% ash content where also an appreciable reduction in the web strength can be observed. All the splitting energies were lower than the one for the base case through the entire solids content and all the conditions show the same shape for the curve.

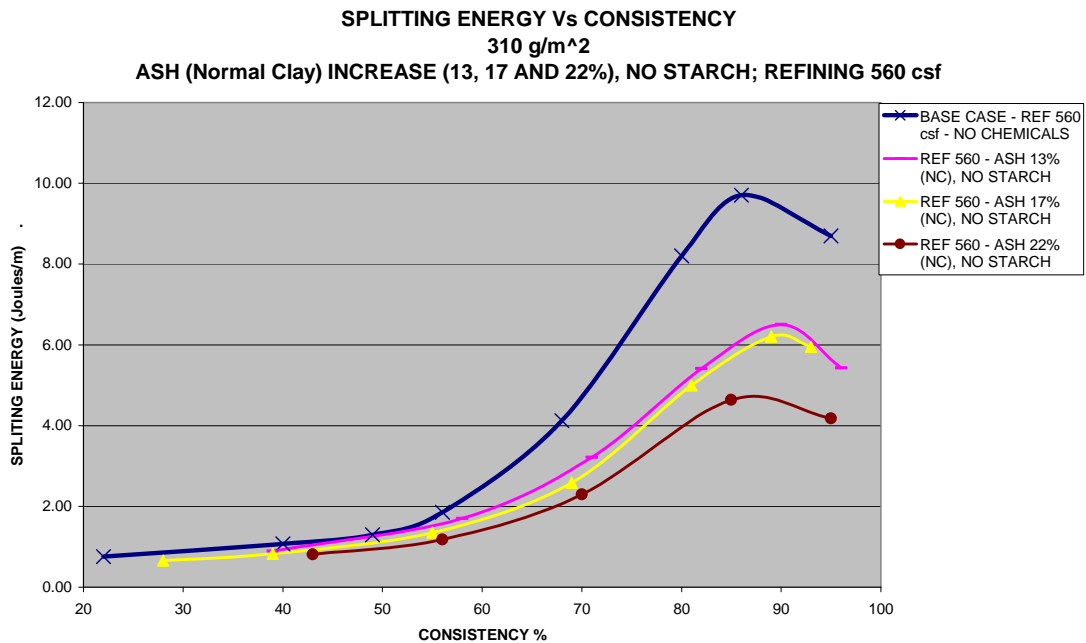


Figure 4.11 – Splitting Energy and Ash Content (Normal Clay Case)

Starch Modified Clay Addition

Figure 4.12 shows the splitting energy variation with three levels of starch modified clay addition obtaining 13, 18 and 24% of ash content and its comparison with the base case. In this situation the basis weight obtained was 318 g/m² (3% higher than the normal clay addition case). Contrary to what happened with the normal clay addition, the splitting energy for solids lower than 55% was almost the same for all the cases. Above 55% solids differences started to show. The base case energy remains the highest, the energies for the 13% and 18% ash content do not seem to be much different (similar situation to normal clay) but when considering the web with 24% ash content a significant reduction results, but still the energy is higher when compared with the normal clay case at the same ash content.

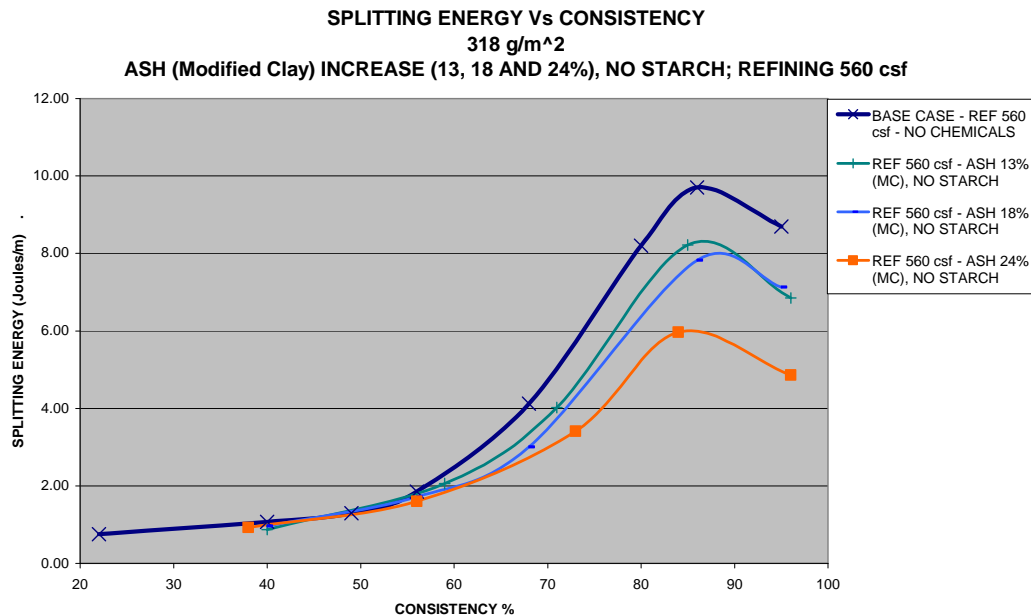


Figure 4.12 – Splitting Energy and Ash Content (Starch Modified Clay Case)

Cationic Corn Starch Effect

Cationic corn starch was added to reinforce the performance of a web obtained when 280 kg/ton of normal clay was added to the furnish. In this case the starch helped to retain the filler and a final ash content of 23% was obtained for an ash retention of 82%. Also the basis weight increased to 340 g/m² (13% more than the base case), this can not be completely explained by an improvement in the retention, so it seems that for these cases additional fiber was used. Two levels of cationic starch were added, 15 and 30 kg/ton. To be able to compare these results against the base case, a graph at a basis weight of 340 g/m² for the three cases was made (Figure 4.13). In this graph it is clear that when 15 kg/ton of corn cationic starch were added, the improvement obtained could not compensate for the strength loss due to the clay addition. When 30 kg/ton of starch was added the situation improves and better results could be obtained through almost the entire solids content, although the highest splitting energy was still obtained with the webs made with no chemicals addition. This shows that the cationic starch helps to improve the splitting energy for wet webs with clay content (the effect tends to diminish as the solids decrease). In the figure it can be seen how for low solids content (below 60%) the web with 15 kg/ton and 23% ash content seems to have higher energy than the base case although it can not be categorically stated to be the case. One reason could be that the effect of the cationic starch is to increase the wet web energy but as the solids go up this positive effect is reduced by the interference that the clay particles offer to the bonding formation.

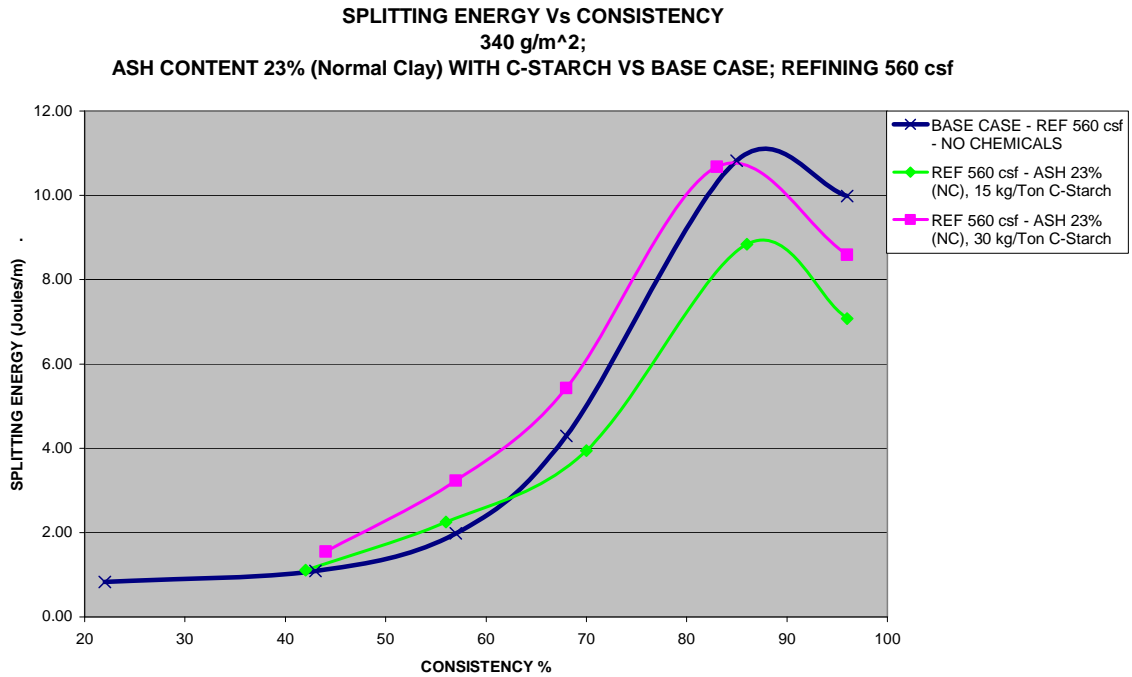


Figure 4.13 – Starch Effect Over Webs with 23% Ash (Normal Clay)

When 15 kg/ton of cationic starch was added to the base case the splitting energy increased above that obtained in the base case. This can be seen in Figure 4.14. In this case an improvement can be clearly seen in the splitting energy for solids levels from 50% through 95%. Splitting energies in some cases are 1.5 times greater than were obtained for the base case. The improvement seems to disappear as solids decrease. This result agrees with previous studies made regarding the performance of chemicals in the wet web strength as discussed by Pikulik.

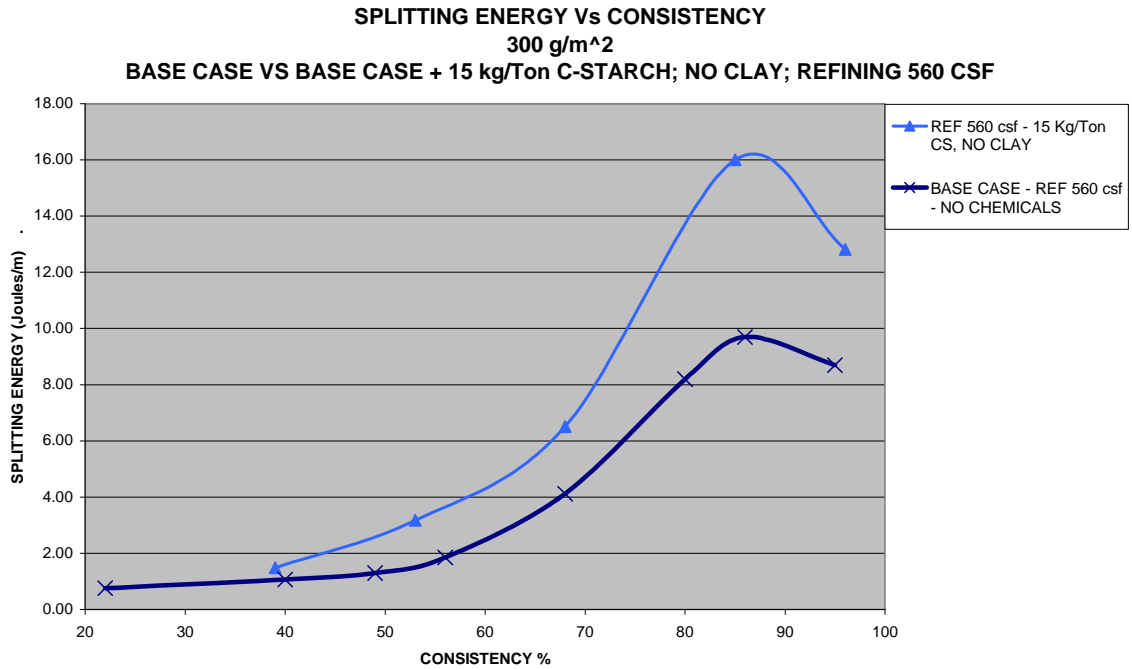


Figure 4.14 – Cationic Starch Effect

Normal Clay Versus Starch Modified Clay Addition

In Figures 4.15, 4.16 and 4.17, the comparison between the performances of the paper obtained when using normal clay versus starch modified clay is presented. In all cases the web obtained using starch modified clay presents higher splitting energies than the webs containing unmodified clay when considering solids above 55%.

For 13% ash content, at solids below 55% all the cases have approximately the same splitting energy. When considering 18% ash content a slight difference can be seen among the three cases. In this situation the splitting energy for the base case and for the starch modified clay remains almost the same, but a small gap can be seen between them and the lower splitting energy obtained when using normal clay. For 23% ash content the situation is similar but the gap is greater. The lower splitting energies obtained with the normal clay at low solids level can be explained because the clay presentation is in suspension form (at 70% solids), with a surfactant added to avoid the clay sedimentation. The surfactants reduce the surface tension of the water and as a consequence the energy that holds the fibers together also go down. The starch modified clay presentation was in powder form and normal water was used to make the suspension preparation so no surface tension reduction resulted. It can be concluded that the effect of the clay over the splitting energy reduction is not as important as the effect of the surfactant for wet web strengths when the surface tension is the dominant mechanism.

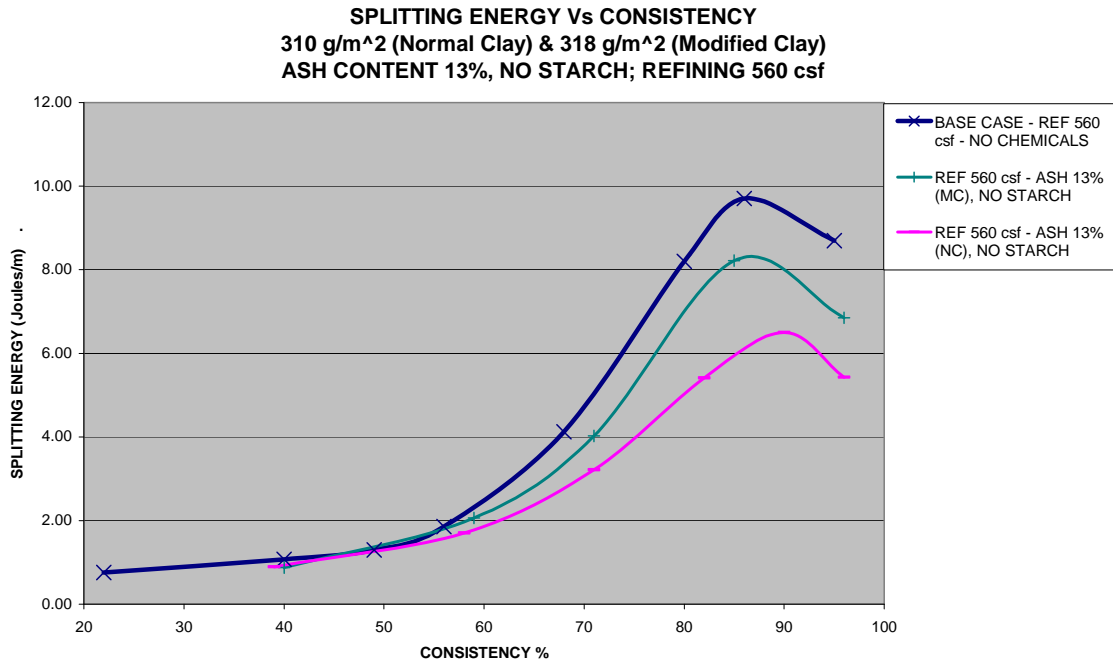


Figure 4.15 – Normal Clay Vs Starch Modified Clay. ASH 13%

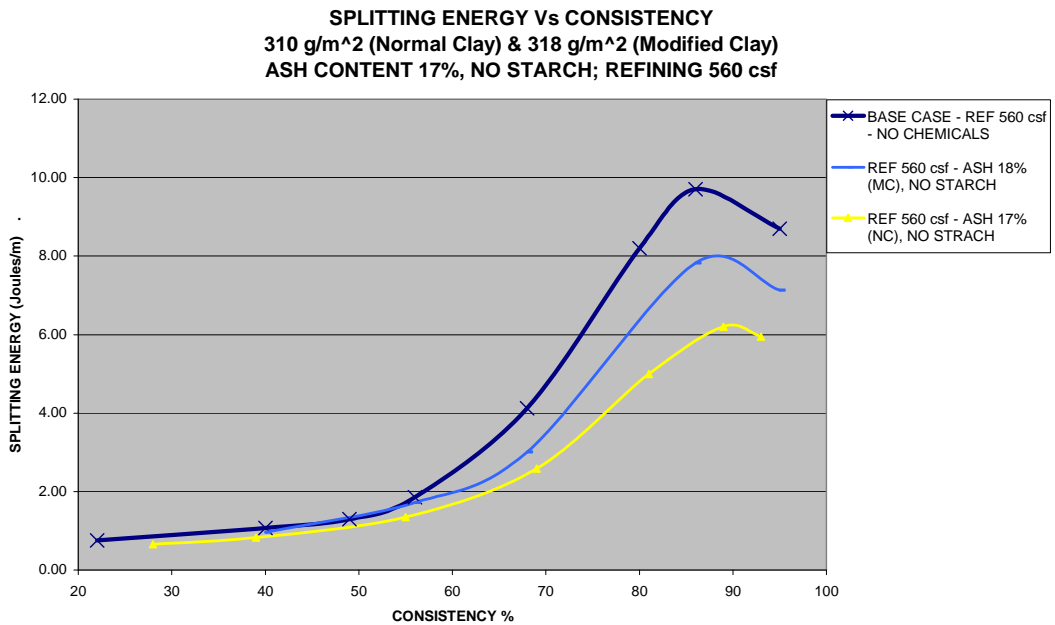


Figure 4.16 - Normal Clay Vs Starch Modified Clay. ASH 17%

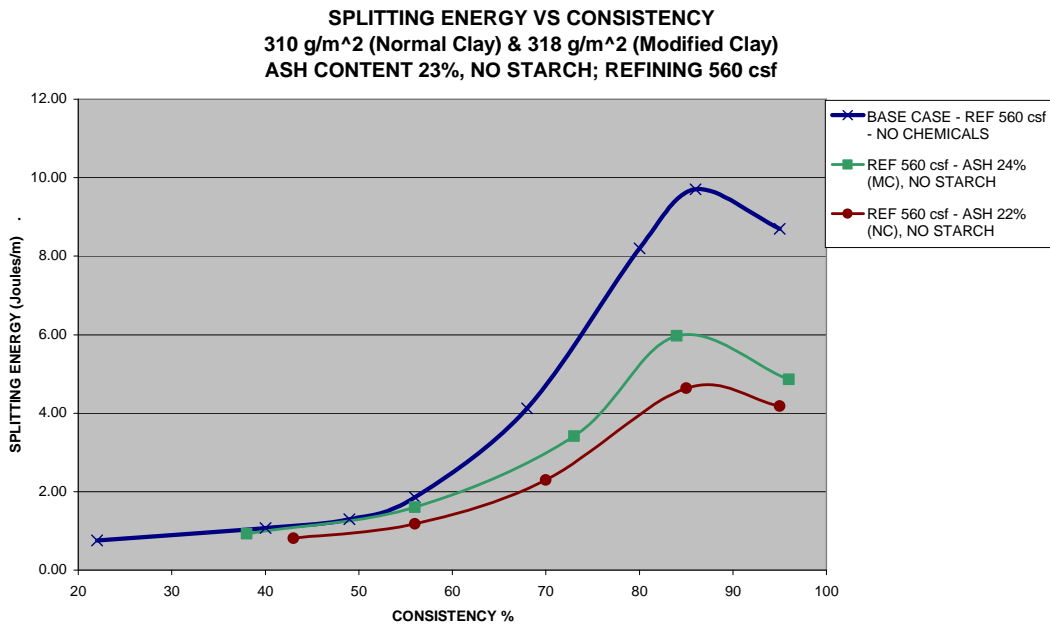


Figure 4.17 - Normal Clay Vs Starch Modified Clay. ASH 23%

Cohesive and Bending Energy determination

Once the splitting energy was found, the next task was to obtain the values for the cohesive and the bending energy. Three different cases (case 1 or base, case 2 or unrefined and case 3 or 17% ash) were considered. For each case four different basis weights were produced. For cases 2 and 3, the basis weights were approximately 100, 200, 300 and 400 g/m². For case 1 the basis weights were around 100, 190, 275 and 340 g/m². In the case of the 100 g/m² webs there is no data at solids level below 40% because the sheets were too weak to support the splitting weights. Graphs for the three cases, similar to that shown in Figure 4.9, are included in Appendix A.2.

As previously stated the splitting energy is higher for webs with higher basis weights. One could assume that the difference in splitting energy between curves at the same solids content is due to the additional energy required to bend the web when a higher amount of fiber is present.

Cohesive Energy Determination

From the data of splitting energy versus solids content for different basis weights, several solids contents were chosen and for each solids level the corresponding splitting energy values were plotted, producing graphs such as that shown in Figure 4.18.

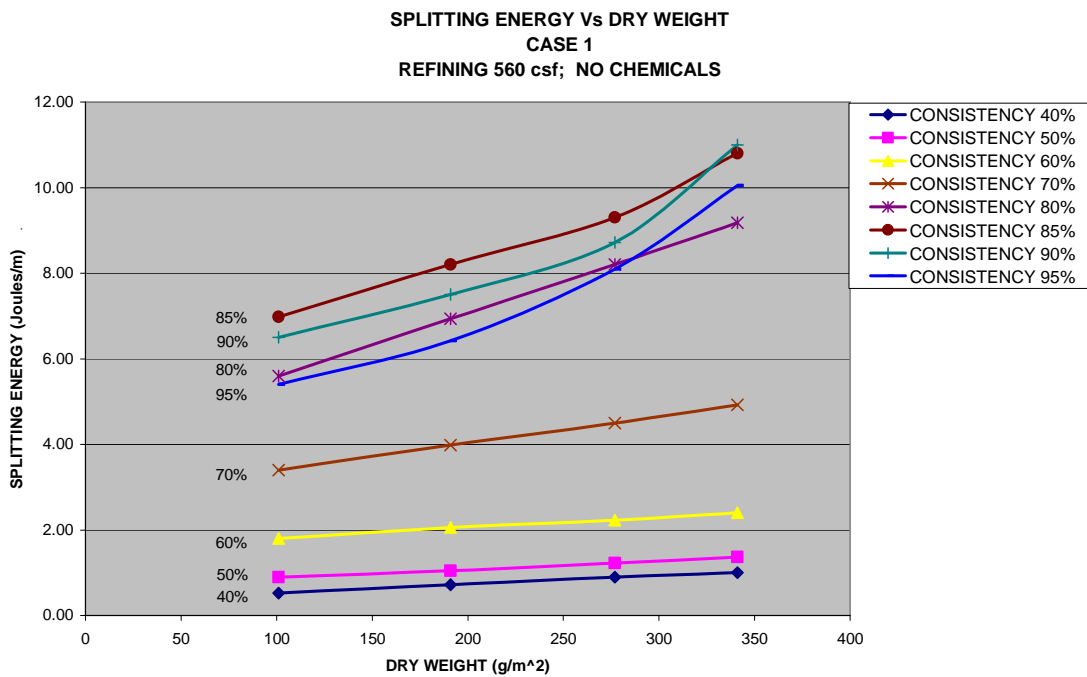


Figure 4.18 – Splitting Energy Vs Basis Weight for Different Consistencies

From this curve it can be seen that the splitting energy behaves linearly with the basis weight for solids up to about 85%, although the slope of the lines are not necessarily the same in all cases. The linearity of the curves was expected, since for each solids content the mechanisms that control the splitting energy are the same, the only difference being the energy needed to bend the web. For solids higher than 85% the curves lose their linearity, especially when considering the higher weights.

It is assumed that the bending energy decreases with basis weight. It is also assumed that the cohesive strength is independent of the web basis weight. Using these two assumptions the cohesive energy can be found. To find the splitting energy at a zero basis weight linear trend lines were fit to the data. Figure 4.19 shows the result for case 1 at consistencies between 40 to 85%. The points were this curves intercepts the Y axis represents the cohesive energy of the paper at its corresponding solids content. At a basis weight of zero the energy required to bend the sheet is zero. The curves for the three cases are in Appendix A.3. In Table 4.6 are the data for the cohesive energy for case 1 to 3.

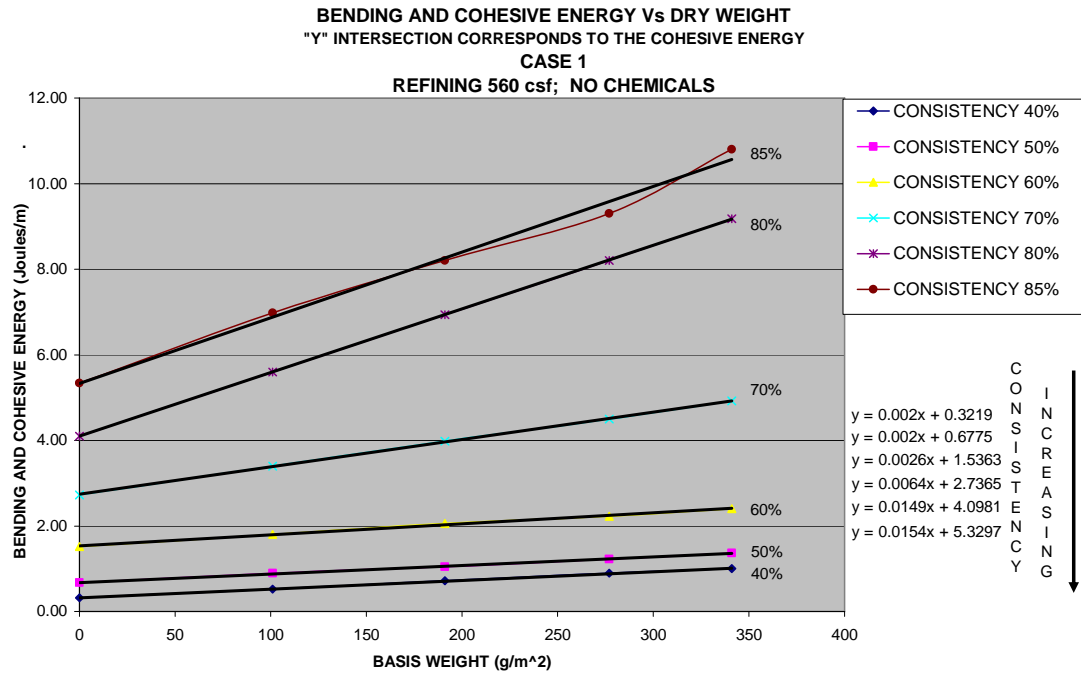


Figure 4.19 – Cohesive Energy Determination

Table 4.6 – Cohesive Energy Cases 1 to 3

CASE DESCRIPTION	COHESIVE ENERGY (J/m)					
	40	50	60	70	80	85
CASE 1: REF 560 csf; NO CHEMICALS - BASE CASE	0.32	0.67	1.52	2.72	4.10	5.34
CASE 2: REF 740 csf; NO CHEMICALS	0.18	0.24	0.38	0.90	2.05	2.85
CASE 3: REF 560 csf; ASH 17% (Normal Clay), NO C-STARCH	0.22	0.50	0.98	1.82	2.98	3.40

The behavior of the cohesive strength versus the solids content for the three cases can be found by considering the data from Figure 4.19 for case 1 and from the equivalent graphs for cases 2 and 3. The results are presented in Figure 4.20. From the graph it is clear how the refined web with no chemical addition reaches higher cohesive energy through the entire solids content range when compared with the other two cases. The refining helps to increase the amount of surface area available to develop fiber entanglement and inter fiber bonding and also makes the fiber more flexible and compactable. A web with little refining web (case 2) will only significantly develop strength when the solids content reaches a point above 65%. Below this value the surface tension effect and the associated fiber entanglement and also the inter fiber bonds created at low solids are not sufficient to improve the strength development. Only after a considerable amount of water is removed from the web does the cohesive strength start to grow exponentially. The mechanical treatment effect is also present in the web with a refining level of 560 C.S.F. and 17% ash content. In this case the cohesive energy starts to grow significantly almost at the same time as the case when no clay is present in the refined web. The difference is that the cohesive values and the growth rate are lower; this may be explained by the interference of the clay particles in the bonding process.

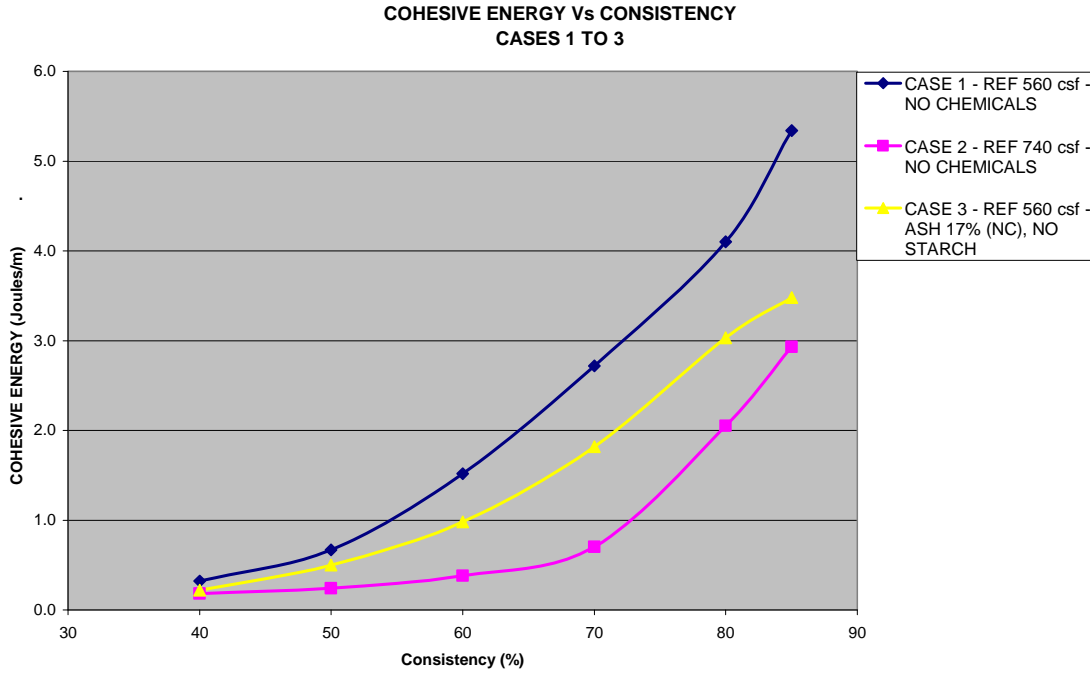


Figure 4.20 – Cohesive Energy Vs Consistency – Cases 1 to 3

Bending Energy Determination

The bending energy is found by subtracting the cohesive energy from the splitting energy. The values for case 1 are presented in Figure 4.21. The curves for all cases are in Appendix A.4.

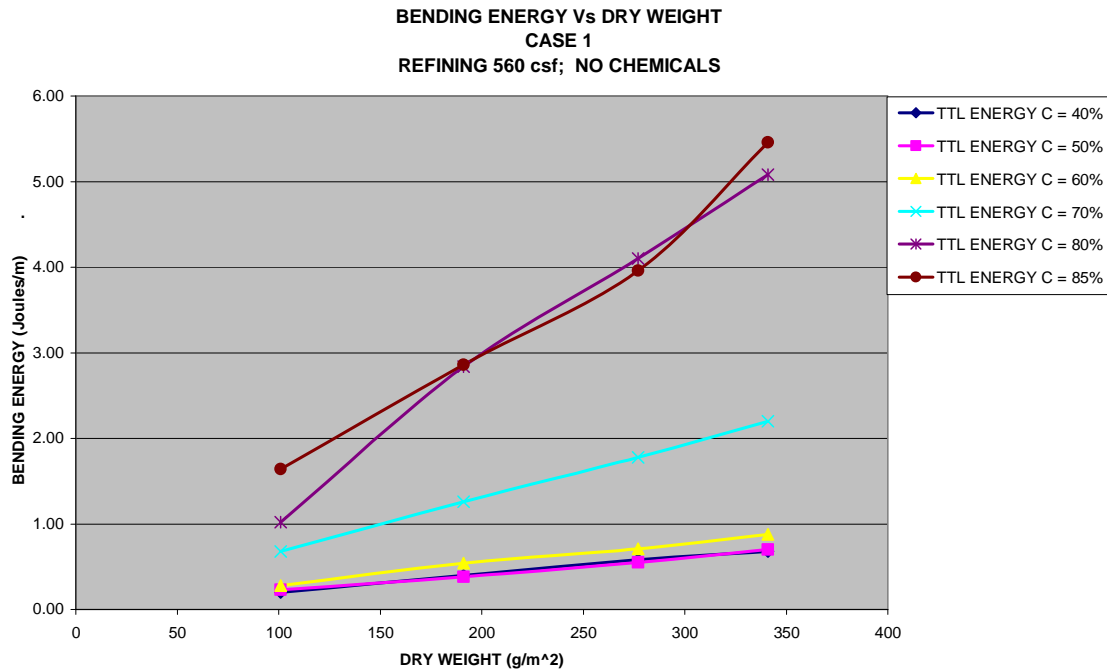


Figure 4.21 – Bending Energy Vs Basis Weight for Different Consistencies

As seen from the above graph there is a linear relation between the bending energy and the basis weight for consistencies from 40 to 85%. The bending energy values for 80 and 85% solids are quite similar, this corresponds to the phase when the total splitting energy begins to decrease.

To be able to compare the variation of the bending energy with the consistency it was necessary to select a basis weight. The situation when the basis weight is 300 g/m² is considered in Figure 4.22 for the three cases.

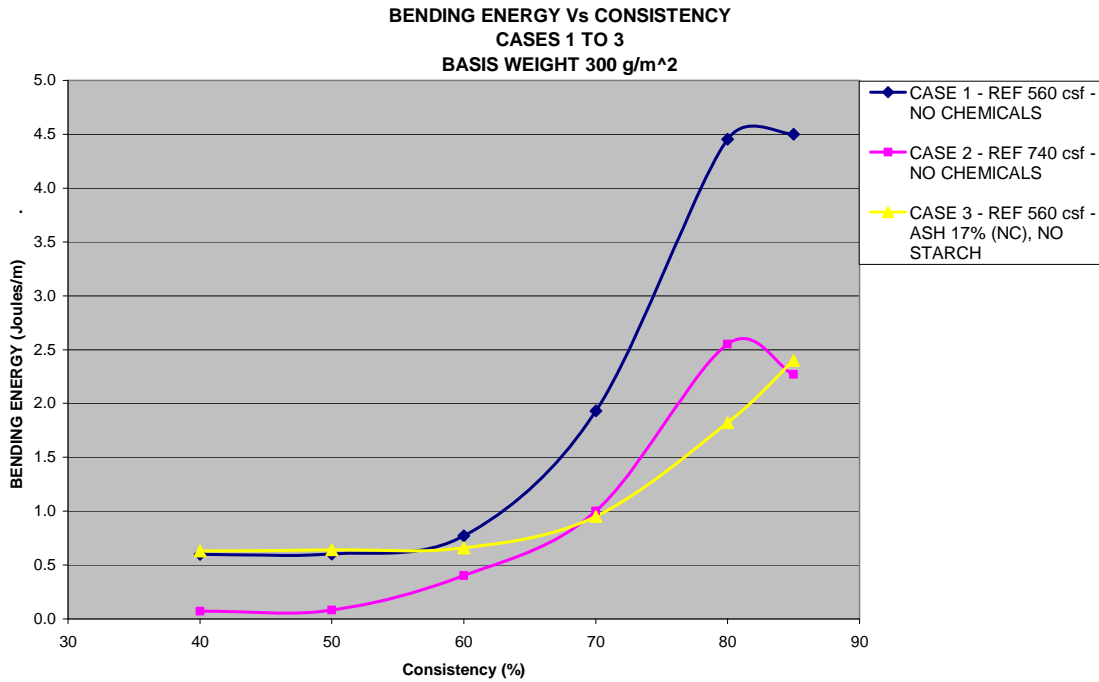


Figure 4.22 – Bending Energy Vs Consistency (Basis Weight = 300 g/m²)

From this graph it can be seen how the bending energy is almost constant for solids below 55% for cases 1 and 3 and below 50% for case 2. It is also clear that the growth rate for cases 1 and 2 is higher than case 3 for solids between 50 and 80%. An interesting fact is that there is a point when the bending energy for case 2 exceeds the one for case 3, this effect did not occur with the cohesive energy.

Tensile Test Results

With two of the twelve strips obtained from each sheet samples were prepared to be tested in the Instron tester. When the testing webs with low solids content were held vertically during the tensile stress, the water moved down in the vertical direction due to

gravity effects. Also when adjusting the jaws to support the test strip, water was displaced from the contact area. Both effects cause variation when using the Instron tester to measure tensile and strength properties. The effects are most significant at low basis weights. It is to be noted that at low solids, i.e., below 50% there is relatively little change in bending or cohesive energy as the solids increase. The differentiation between cases occurs primarily at solids levels above 50% and in this range the tensile tests were less subject to the problems encountered at the low solids levels. All cases were subjected to Instron testing.

Figure 4.23 shows typical stress-strain curves for the base case, for a basis weight of 277 g/m² and different solids level is presented. The graph shows the average result of all the strips that were tested under these conditions. At least 4 strips were tested for all cases. In Appendix E.1 are the stress-strain curves for all the cases. From these graphs the maximum tensile load and the strain at the maximum tensile load can be obtained to determine how the tensile strength and the strain vary with the solids content. From Figure 4.23 it is clear that at low solids, the web supports less load and also displaces less before rupture. As solids go up so does the load and displacement before rupture. Eventually a point is reached when the load before rupture keeps on going up but the displacement at the rupture points starts to go down.

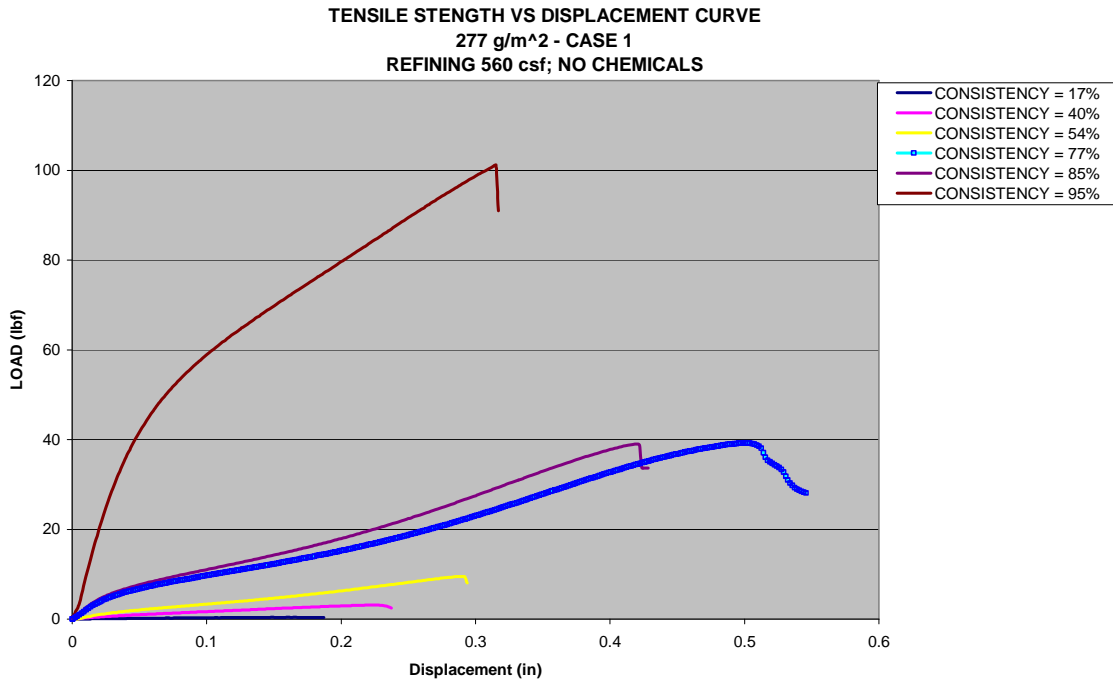


Figure 4.23 – Stress-Strain Curve Base Case

In Figure 4.24 are the results for the maximum tensile load at different solids for cases 1 to 3. In Appendix E.2 are the graphs for the other cases. For values lower than 45% solids there is no difference among the values, after this point the maximum tensile load for case 1 is higher, followed by case 3 and the lowest value corresponds to the unrefined web.

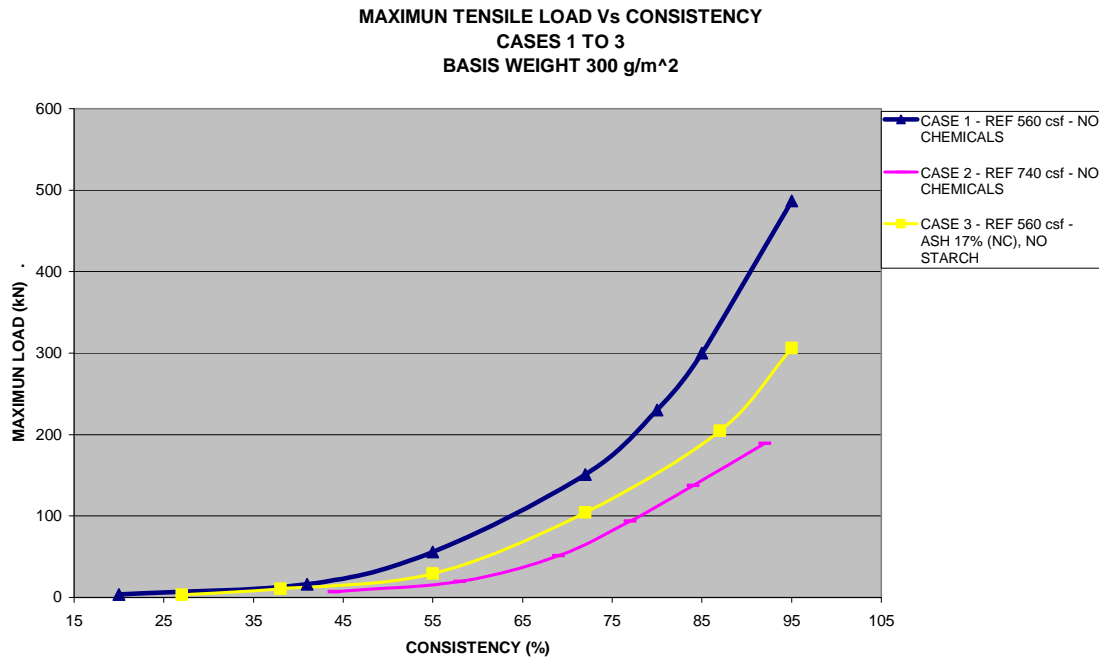


Figure 4.24 – Maximum Load Vs Consistency

In Figure 4.25 are the results for the measured percent strain at the maximum tensile load for cases 1 to 3. In Appendix E.3 are the graphs for the rest of the cases. The lower values of percent strain correspond to the webs with low solids, there is a maximum percent of strain at solids between 75 and 85% and then the percent of strain goes down. The webs with mechanical treatment deform more than the unrefined web, this can be explained because the refinement increases the bonding area of the fiber so it can support more strain before rupture.

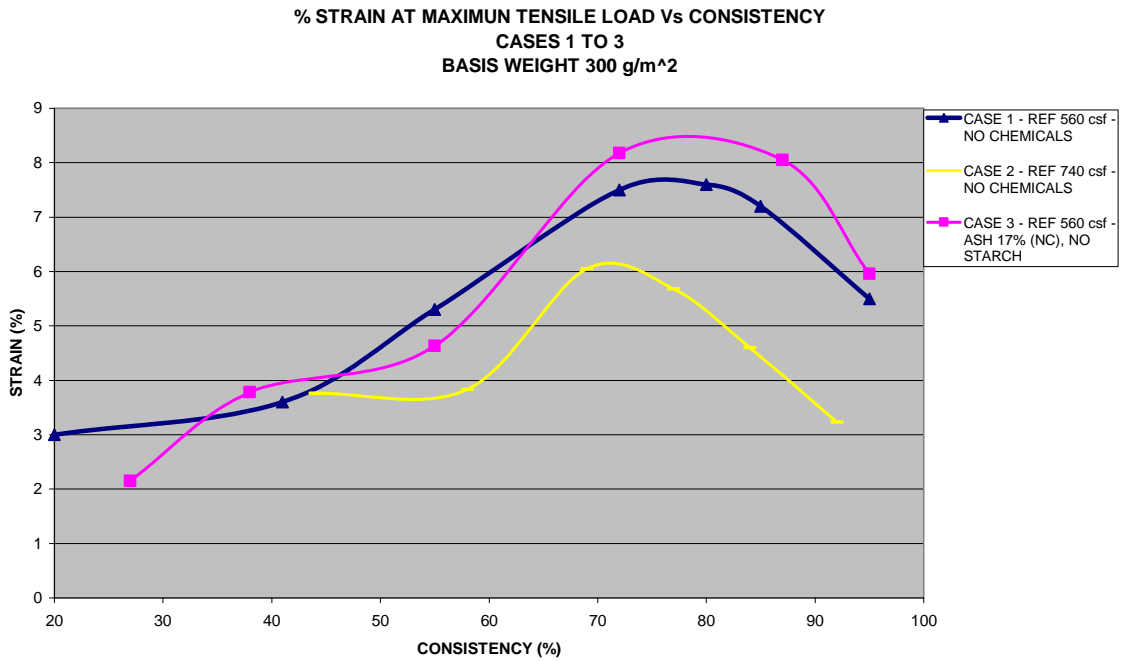


Figure 4.25 – % Strain at maximum Load Vs Consistency (Instron)

The same comparisons that were performed for the splitting energy variation with the mechanical and chemical treatments can be found in Appendix E.2 and E.3 for the tensile maximum load and for the strain at maximum tensile load respectively. The pulps refined to 440 and 560 C.S.F. behave similar to each other and much better than the unrefined pulp. The increase in ash content (obtained with normal clay or starch modified clay) reduces the tensile strength but the effect is not as great as obtained with the splitting test. The webs with starch modified clay also present better results than the ones that have normal clay. The cationic starch addition also helps to improve the paper tensile resistance but again the effect is not as great as obtained with splitting strips. Each one of the cases support the conclusions previously made for the splitting test results.

In Figure 4.26 is the graph relating the maximum tensile load for the different basis weights for case 1, the graph for the three first cases can be seen in Appendix E.4. From the graph it can be seen how for solids values less than 40% it is hard to establish a difference between the tensile strength and the basis weights

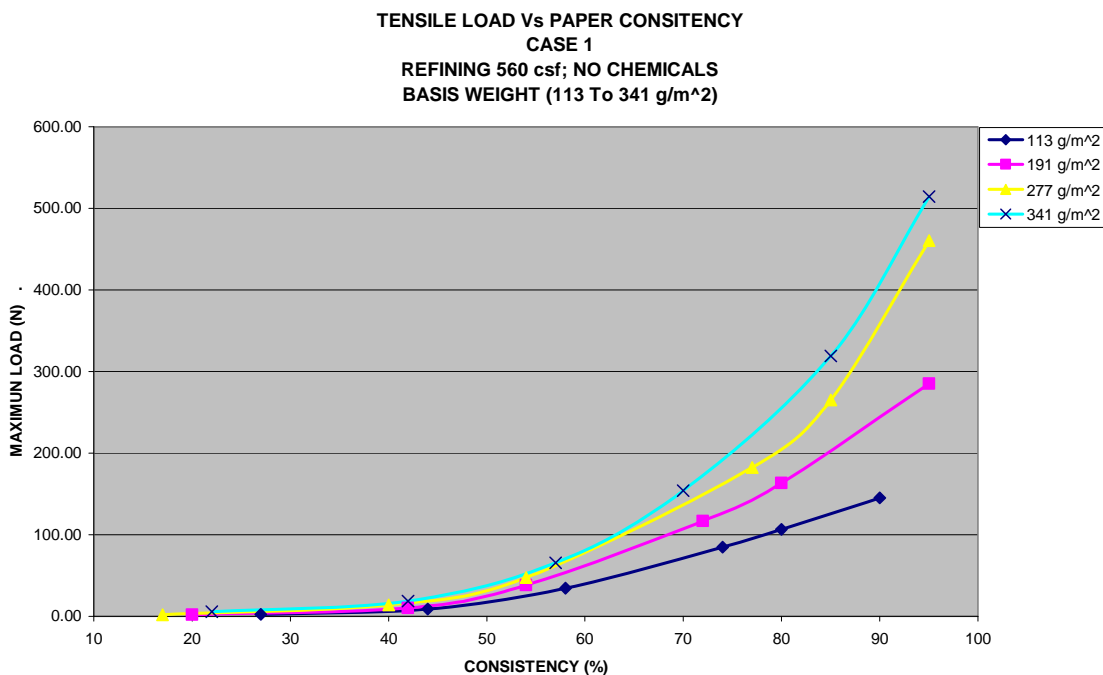


Figure 4.26 –Tensile Strength Vs Basis Weight for Case 1

Envelope Curves

Envelope curves for cases 1, 2 and 3 are shown in Figure 4.27. Similar graphs for the other cases are in Appendix F. Based on the idea that for the same tensile strength the web with the higher stretch will run better or for webs with the same stretch the web with higher tensile strength will run better, it can be observed that for consistencies below 70% there is no major difference. However, as soon as the solids go higher than 70% the unrefined pulp shows poor performance, while the other two cases are similar and at the end for higher solids the web without chemicals will perform better. When making the comparison for the different refining levels it is clear that the pulp refined to 440 C.S.F. will perform better than the other two conditions over all the solids considered, as shown in Figure 4.28. The rest of the conditions do not give any other more valuable information.

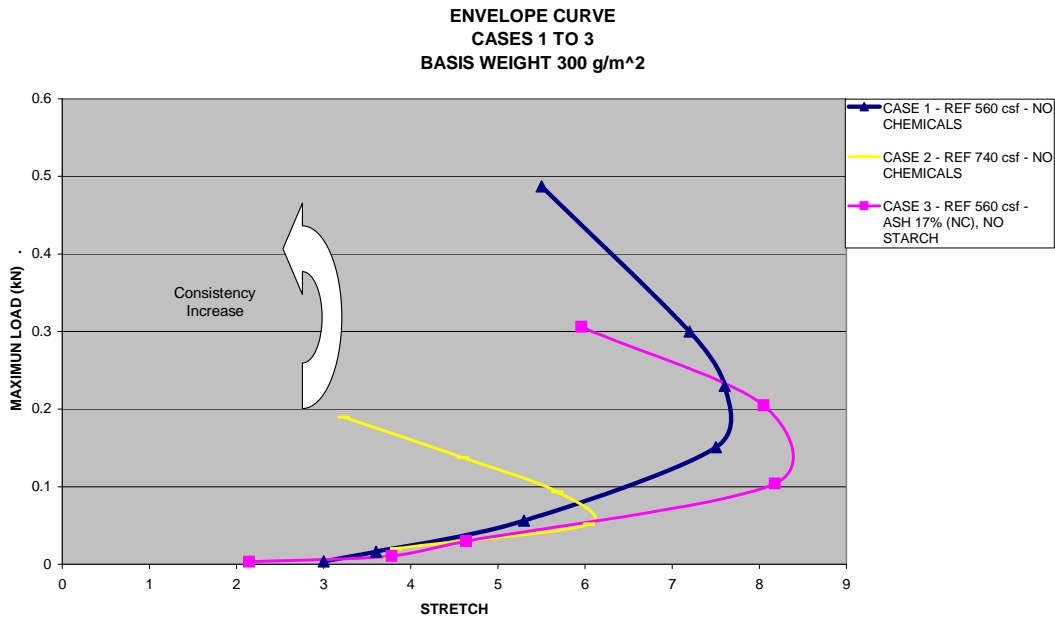


Figure 4.27 – Envelope Curve Cases 1, 2 and 3

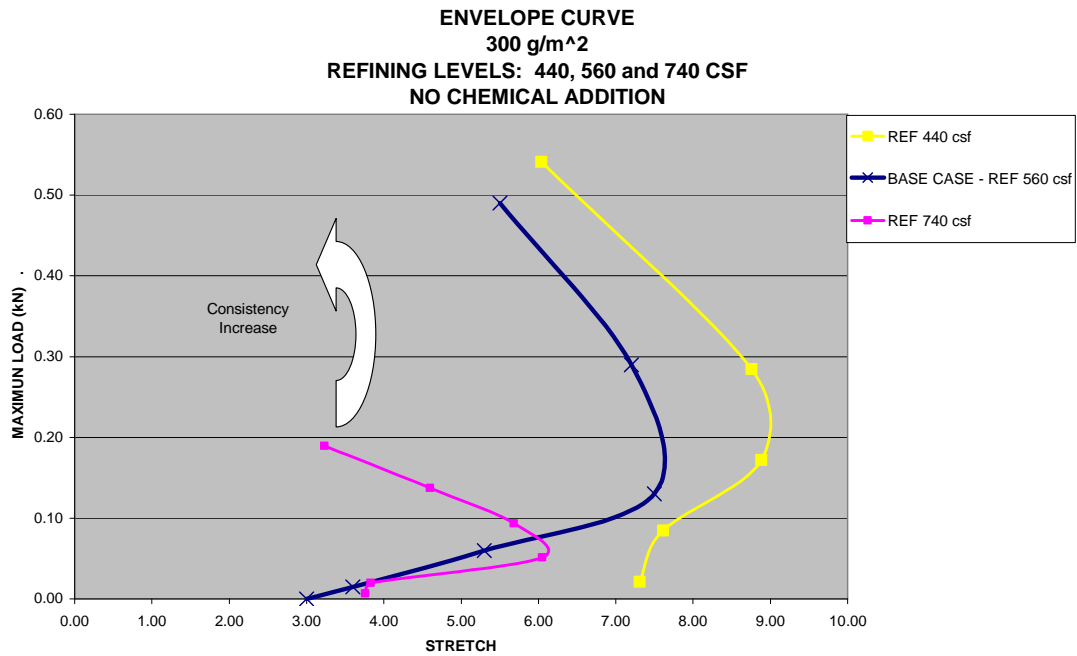


Figure 4.28 – Envelope Curves for Different Refining Levels

Splitting Energy Results Validation

Page Equation for Wet Webs

It has been established that the tensile strength depends, in part, on the internal energy that bonds the fibers together in the web. This internal bond strength is related to the cohesive energy found previously for cases 1, 2 and 3.

As previously discussed, Williams and Page dealt with the issue of determining the relation between the tensile index and the shear strength of the fiber to fiber bond for wet webs, starting with the known relation between both factors (eqn 2.2) for chemically pulped softwood made dry sheets. For wet webs the strength depends on the fiber to fiber interaction and the strength of the bonds in the area of contact. During the tensile test of wet webs, the fibers are not broken. In this case it can be assumed that for sheets made of straight fibers weakly bonded (low solids content) the fiber strength by far exceeds the bond strength or $Z \gg b$ in equation 2.2. Based on this assumption equation 2.2 takes the form of equation 2.3. In our case the tensile strength can not be determined using Page equation 2.3 because in that equation it is necessary to find b (the shear strength of the fiber to fiber bond). Equation 2.3 also shows that there exists a constant linear relation, defined by the value K , between the tensile index and the shear strength of the fiber to fiber bond. The expression for K is given by the expressions in equation 4.1 and 4.2.

$$\frac{1}{T} = \frac{9}{8Z} + \frac{12C}{bPL_f RBA} \quad 2.2$$

$$T_{ww} = (bPL_f RBA_{ww}) / 12C \quad 2.3$$

$$K = (PL_f RBA_{ww}) / 12C \quad 4.1$$

$$T = Kb \quad 4.2$$

With the splitter apparatus the cohesive energy measured is not the same as would be measured in a test which subjects the sheet to a pure shear loading. Such a test would be required to directly determine b . However the cohesive energy is controlled in part by fiber to fiber bonding and it could be expected that the two are directly related. Therefore, it should be possible to use the Page model to develop a relationship between tensile index and cohesive energy index. To investigate the relationship a comparison of the two parameters was made for cases 1, 2 and 3 at a basis weight of 300 g/m^2 and for different solids content. Data for different consistencies were collected from Figures 4.20 for the cohesive strength and from Figure 4.24 for the maximum tensile strength, these data were then divided by the sample width (2" for cohesive and 1" for tensile indices respectively) and the result divided by the basis weight of the web (300 g/m^2) to obtain the cohesive strength index and the tensile strength index at several solids. The data are shown in Tables 4.7 and 4.8 and presented in Figure 4.29. The values for case 1 corresponding to 300 g/m^2 was obtained interpolated the actual measurement for this case (277 and 341 g/m^2).

In the graph a linear relationship is observed for all the cases, implying that there exists a relation between the tensile strength index and cohesive strength index as could be assumed from the Page equation for wet webs. Another factor that supports the application of Page model is the fact that all the curves tends to zero when the cohesive strength tends to zero. A value of zero cohesive strength corresponds to a value of zero solids content or an ideal completely wet web.

It is not clear at what solids content Page wet web model must be changed from the one described by equation 2.3 to the one of a dry sheet described by equation 2.2. What can be stated from the results in this thesis and considering the data obtained for the cohesive and tensile strength for consistencies below 40%, is that for values less than this the linear relation between the tensile and cohesive indices still applies as clearly applies for values greater than 40%.

The other result that is of interest is that the slopes of the curves are almost the same for all cases (108).

Table 4.7 – Tensile Strength Index Data – 300 g/m² (Measured on Instron)

TENSILE STRENGTH INDEX [Nm/g] VS CONSISTENCY						
CASE	40	50	60	70	80	85
CASE 1: REF 560 csf; NO CHEMICALS	1.84	4.72	9.84	19.03	30.18	38.71
CASE 2: REF 740 csf; NO CHEMICALS	1.04	1.56	3.13	7.56	14.60	18.51
CASE 3: REF 560 csf; ASH 13% (NC), NO STARCH	1.27	2.53	5.82	12.03	19.24	24.05

Table 4.8 – Cohesive Energy Index Data – 300 g/m² (Measured on Splitting Apparatus)

CASE	COHESIVE ENERGY INDEX [Nm/g] VS CONSISTENCY					
	40	50	60	70	80	85
CASE 1: REF 560 csf; NO CHEMICALS	0.02	0.04	0.10	0.18	0.27	0.35
CASE 2: REF 740 csf; NO CHEMICALS	0.01	0.02	0.02	0.06	0.13	0.19
CASE 3: REF 560 csf; ASH 13% (NC), NO STARCH	0.02	0.03	0.06	0.12	0.19	0.22

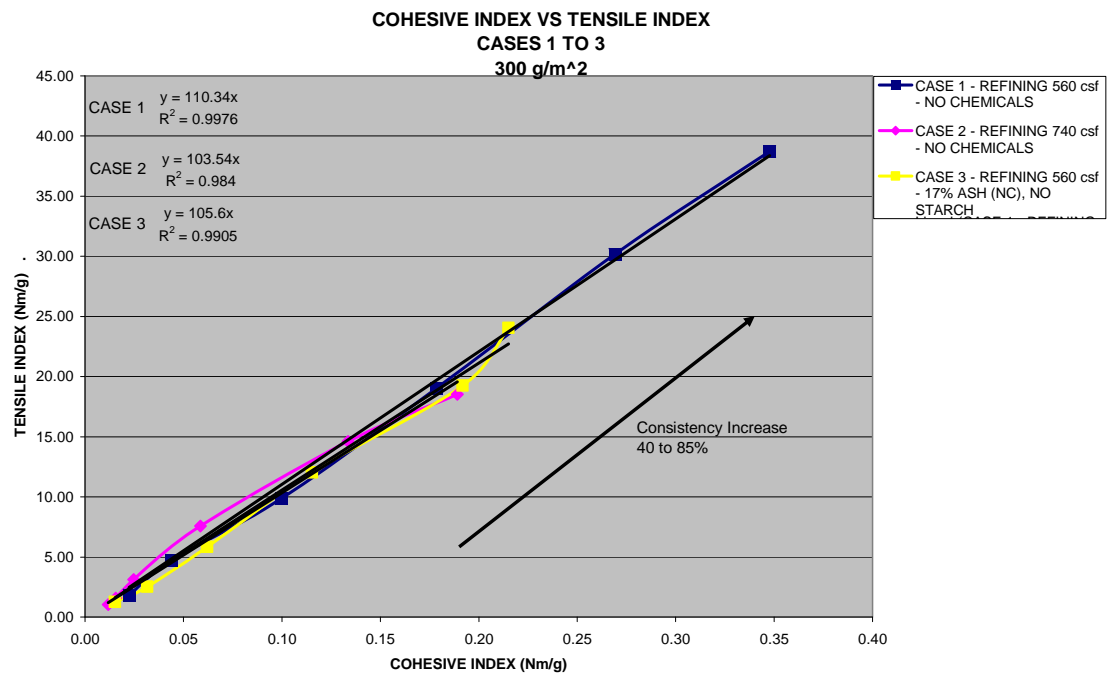


Figure 4.29 – Cohesive Strength Index Vs Tensile Strength Index for Cases 1 to 3

Another verification that can be done to the relation between the cohesive and tensile index is comparing them considering different basis weights but the same mechanical and chemical treatment. From the graphs for cases 1 to 3 for the tensile strength variation versus solids content for the different basis weights and from the equivalent graphs for the cohesive energy the data for Table 4.9 and 4.10 can be obtained for case 1, the data for all the cases are in Appendix G. With these data the indices relation graphs presented in Figure 4.30, 4.31 and 4.32 for case 1, 2 and 3 was made. It can be seen how for the different basis weights linear relations can be established between the indices in the solids range considered in the graphs (40 to 85%). From the results of cohesive and tensile strength for solids lower than 40% it is also clear that the linearity of the indices ratio still applies.

In the range from 40 to 85% solids the relation between the indices seems to be basis weight dependent. If we consider the relation for values less than 40% the situation is different, for this range the values for all the basis weight are similar as can be concluded by analyzing the behavior of all the cohesive and tensile strength curves versus solids content, this allows to conclude that for this solids range the relation between the indices is not weight dependent.

Table 4.9 – Tensile Strength Index Data for All Basis Weights – Case 1

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
101	1.95	7.02	15.59	27.29	40.93	48.73
191	1.65	5.15	12.37	22.26	34.01	42.05
277	1.71	4.55	9.95	19.61	29.28	37.66
341	1.73	4.50	9.24	17.90	29.44	36.95

Table 4.10 – Cohesive Energy Index Data for All Basis Weights – Case 1

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
101	0.06	0.13	0.30	0.53	0.80	1.04
191	0.03	0.07	0.16	0.28	0.42	0.55
277	0.02	0.05	0.11	0.19	0.29	0.38
341	0.02	0.04	0.09	0.16	0.24	0.31

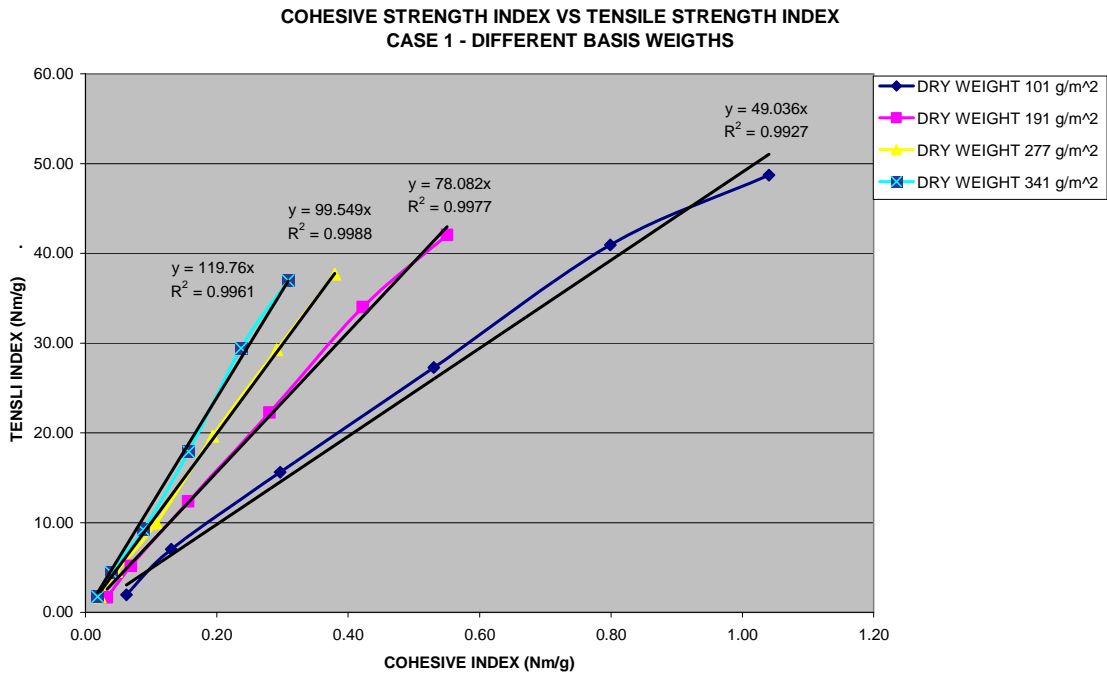


Figure 4.30 – Cohesive Vs Tensile Strength Indices for Case 1

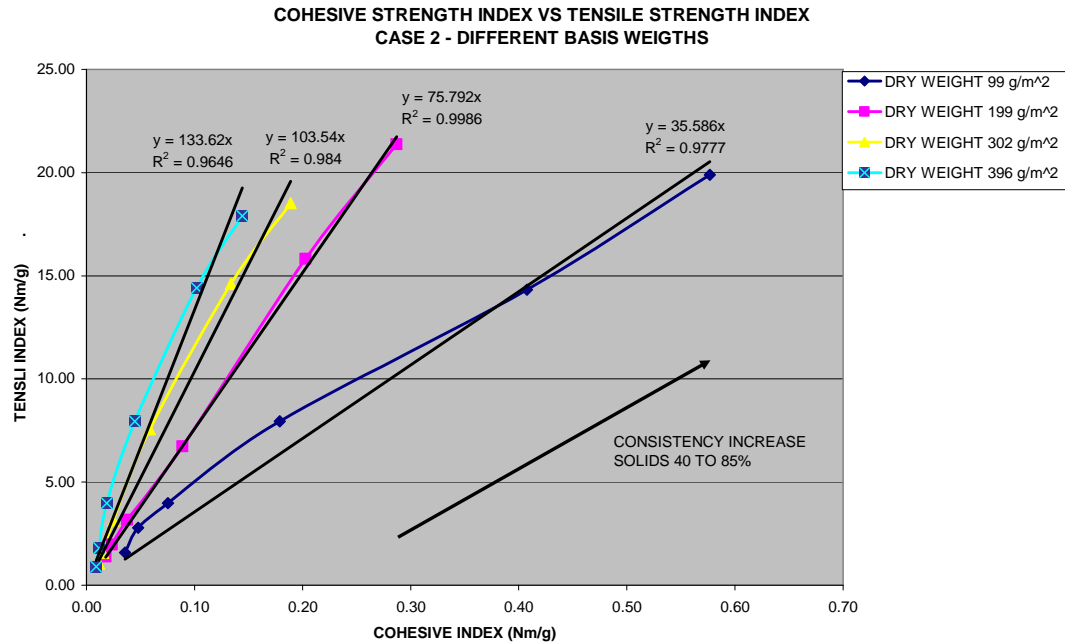


Figure 4.31 – Cohesive Vs Tensile Strength Indices for Case 2

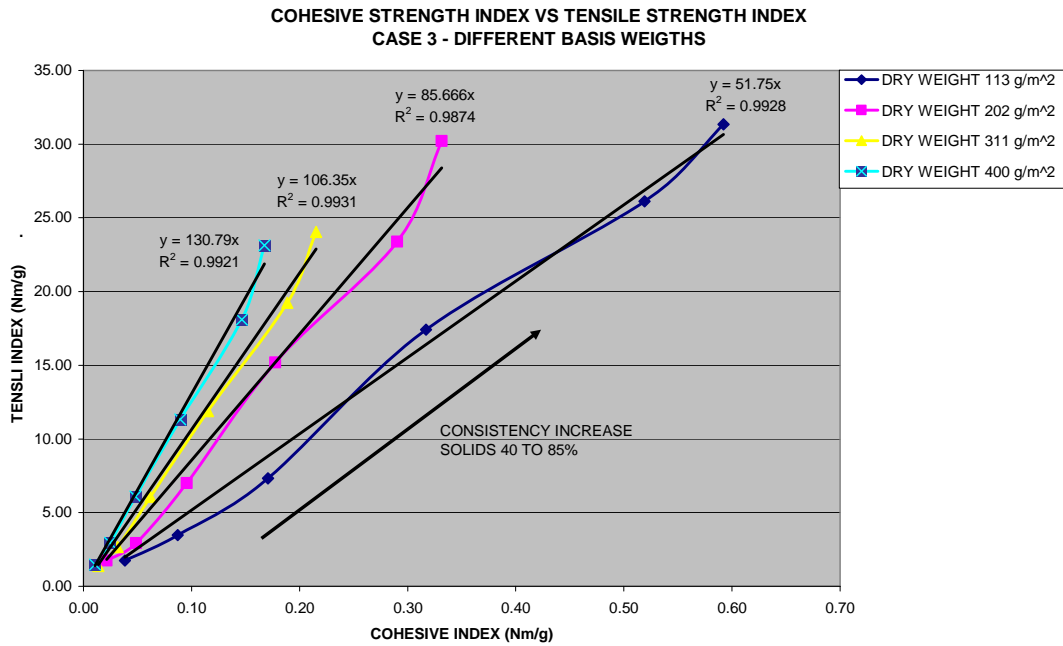


Figure 4.32 – Cohesive Vs Tensile Strength Indices for Case 3

In Table 4.11 is a summary of the slopes obtained for every case and every basis weight. The values for case 1 corresponding to 400 g/m² was obtained extrapolated the actual measurement for this case. As can be seen from the table the values for all the cases are similar within the different basis weights.

Table 4.11 – Cohesive Vs Tensile Index Relation

	100 g/m ²	200 g/m ²	300 g/m ²	400 g/m ²
CASE 1	49	78	110	139
CASE 2	37	75	103	134
CASE 3	51	85	105	130

If for every case the data from the previous table are plotted against the basis weight, a linear relation between the different slopes can be established. In Figure 4.33 such a graph is presented. It is interesting to see how the slopes of the curves for cases 1 and 2 are the same ones, this can be explained because no filler was used in these cases. On the other hand the slope for case 3 is different and lower. In addition if all the slopes were taken together to establish a general relation valid for all the cases, the Figure 4.34 is obtained. In this graph a linear relation can also be established between all the data.

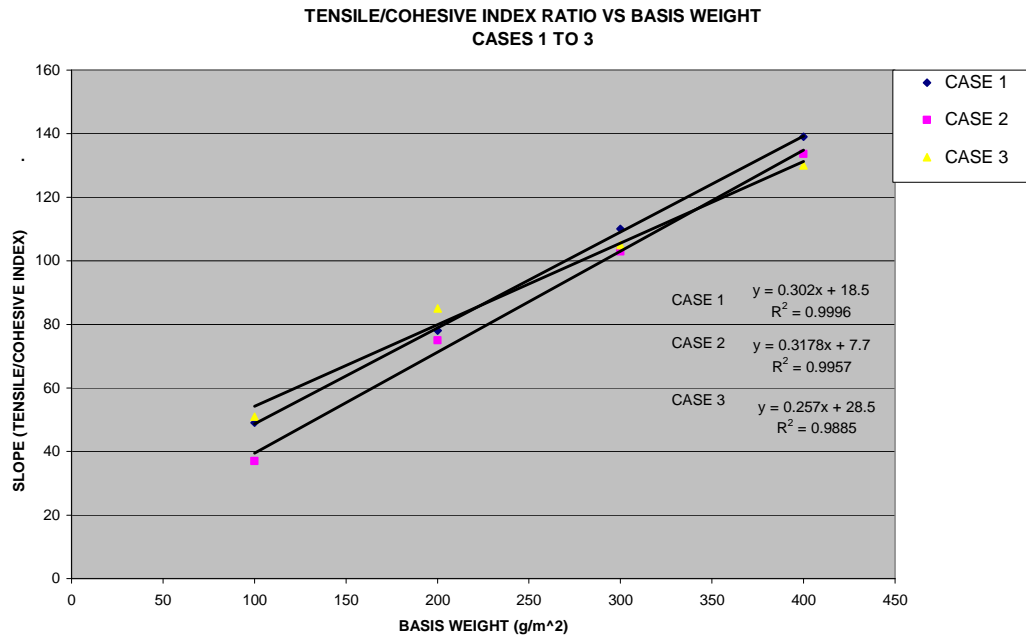


Figure 4.33 – Tensile/Cohesive Index Ratio Vs Basis Weight. Cases 1, 2 and 3

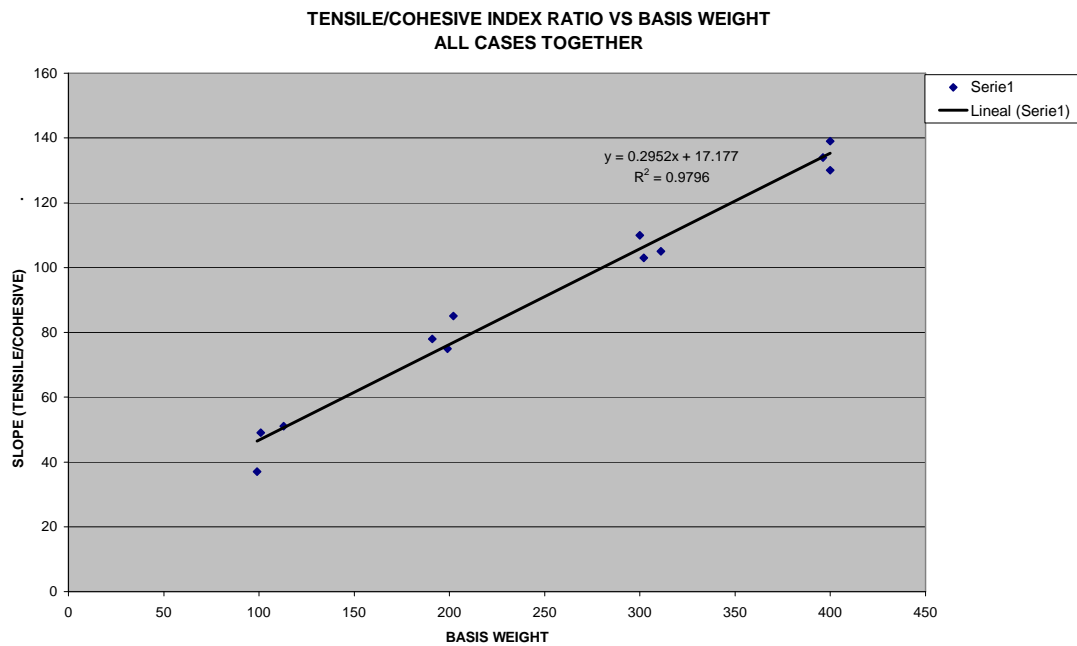


Figure 4.34 – Tensile/Cohesive Index Ratio Vs Basis Weight. All Cases

Although it is not clear why the slopes for all the basis weights within the same cases are different, a linear relation among all the basis weights can be easily established that makes it possible to superimpose all the tensile and cohesive indices ratio of the different basis weights for every case. The correction factors that can be used to superimpose the index relation curves for case 1 on the higher basis weight are shown in Table 4.12 using the data obtained from Figure 4.34 and the graph showing the original results and the superimposed ones are in Figure 4.35. The graph shows an almost perfectly superimposed result.

Table 4.12 – Index Ratio Correction Values for Case 1

	BASIS WEIGHT (g/m²)			
	101	191	277	341
ORIGINAL VALUE	49	78	99	120
CORRECTION FACTOR	2.51	1.62	1.19	1.00
CORRECTED VALUE	123	126	118	120

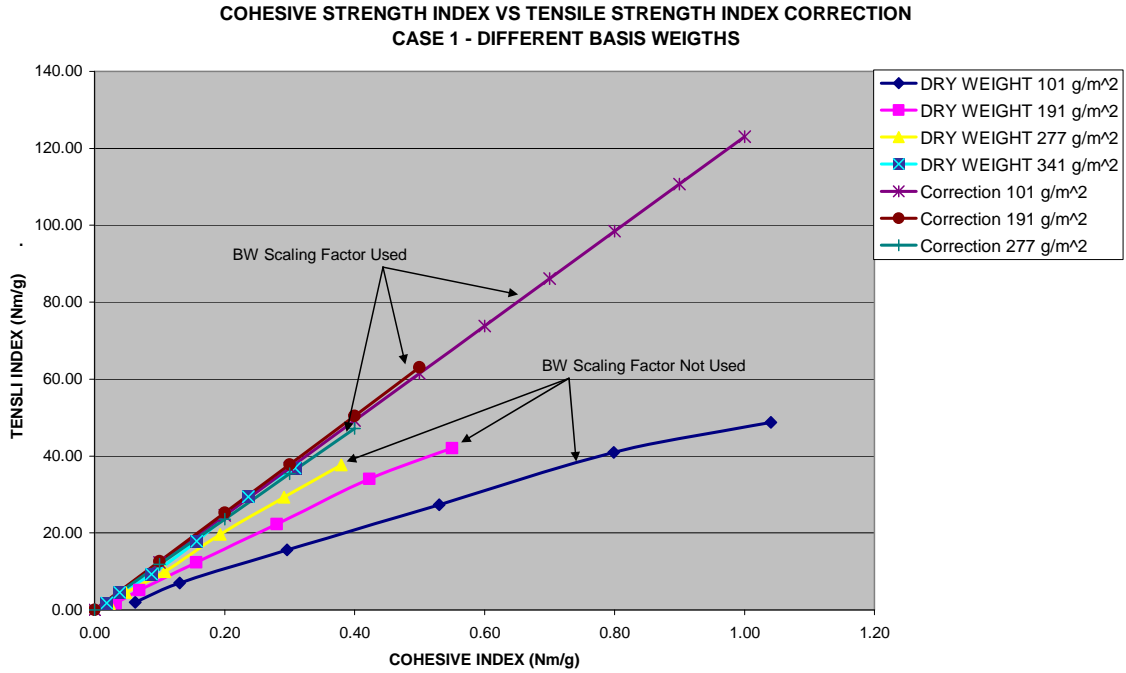


Figure 4.35 – Corrected Tensile/Cohesive Indices Ratio

Osterberg Strain Calculation

Osterberg equations, originally developed to model the process of separation of two surfaces, can be used to determine the strain occurring in the strip during the splitting test. Equation 2.7 obtained by Osterberg shows the relation between the total work performed to the paper during the separation process, while equation 2.12 represents the work of separating the two surfaces. Both expressions are related through equation 2.8. Since during the test the splitting angle (or take off angle) is 90°, the Osterberg equation 2.7 reduces to equation 4.4, while equation 2.12 reduces to equation 2.13. These equations relate the work of separation for two surfaces with the tension, basis weight, velocity of the crack propagation, tension applied to the strip and strain.

$$W_T = (T_w - m_w V_w^2)(1 - \cos\theta) + T_w \epsilon + m_w V_w^2 \epsilon \cos\theta \quad 2.7$$

$$W_S = (T_w - m_w V_w^2)(1 - \cos\theta) + T_w \epsilon - m_w V_w^2 \epsilon(1 - \cos\theta + \epsilon/2) - T_w \epsilon/2 \quad 2.12$$

$$W_T = W_S + W_E + W_M \quad 2.8$$

Assuming a take off angle of 90°

$$W_T = (T_w - m_w V_w^2) + T_w \epsilon \quad 4.4$$

$$W_S = (T_w - m_w V_w^2) - m_w V_w^2 \epsilon(1 + \epsilon/2) + T_w \epsilon/2 \quad 2.13$$

Note that the main difference between these two equations is that 2.13 subtracts out a momentum term and one half of the strain term.

Solving equation 4.4 for ϵ we obtain

$$\epsilon = (W_T + m_w V_w^2 - T_w)/T_w \quad 4.6$$

Solving equation 2.13 for ϵ we obtain

$$(m_w V_w^2/2) \epsilon^2 + (m_w V_w^2 - T_w/2) \epsilon + (W_S + m_w V_w^2 - T_w) = 0 \quad 4.5$$

To explain the procedure the data from the splitting test of a wet web at 41% solids corresponding to a basis weight of 277 g/m² and refined to 560 C.S.F. is considered. To solve these equations we need to find:

1. Tension: It is necessary to find the acceleration of the system and multiply this value by the total splitting weight, the result is divided by the strip width. The

acceleration depends on the splitting weight and on the splitting energy of the paper strip. As shown in Figure 4.36 the change in velocity is constant with time and the acceleration is a constant with time. This in turn means that the tension is constant with time. In this particular case the acceleration is equal to 6.74 m/s^2 . The total splitting weight is 1.1 kg and the tension is 7.41 N . The force is applied over a strip $2''$ width and the tension per unit width is 146 N/m .

2. W_S or W_T : The work of separation of the surfaces (W_S) or the total work done to the paper (W_T) are related to the cohesive energy of the paper. The value previously found (in J/m) is divided by the strip width ($2''$) to find the work per unit area in N/m . For this particular case the work of separation is 6.3 N/m .
3. $m_w V_w^2$: m is the basis weight of the paper in kg/m^2 . The velocity of the crack propagation increases during the splitting of the web providing that enough stored initial energy (enough splitting weight) is available to overcome the friction and the splitting energy of the strip. For this particular case the velocity variation during the crack propagation is shown in Figure 4.37. The relationship is linear which corresponds with the result that the variation in velocity with time is also linear

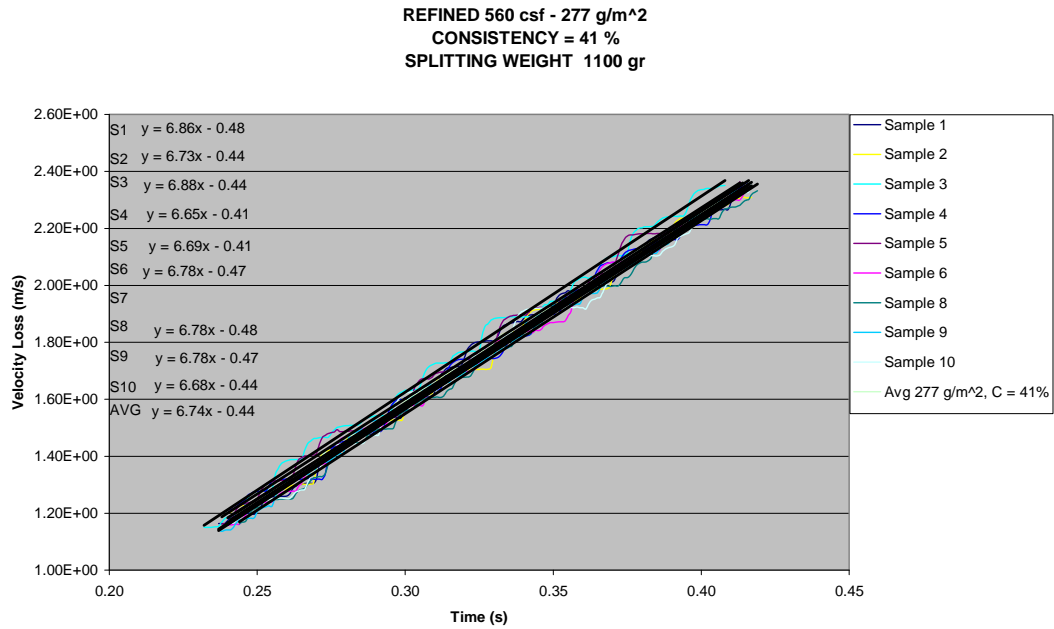


Figure 4.36 – Splitting Velocity Vs Time

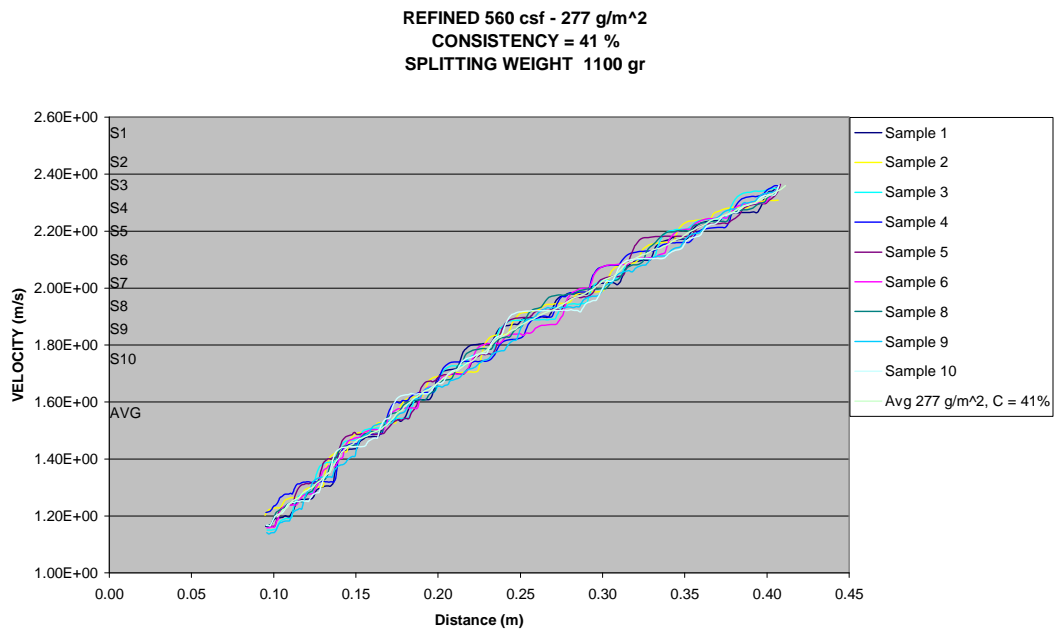


Figure 4.37 – Velocity Increase Vs Crack Propagation

Considering each one of the values through the entire test and solving for ϵ in both equations Figure 4.38 can be made for consistencies below 72% solids. The strain value obtained increases through the solids content considered. The values for the strain obtained from equation 4.6 (W_T) are around two times greater than the values obtained from equation 4.5 (W_S). The strain increased with the solids content, this can be explained for low solids because there is not enough force to keep the fibers together. While the solids go up more internal strength can keep the fibers together and the web will support more strain before failure. In Figure 4.39, the data for Osterberg strain based on the work of separation of the two surfaces (W_S) can be observed for solids from 40 to 75%.

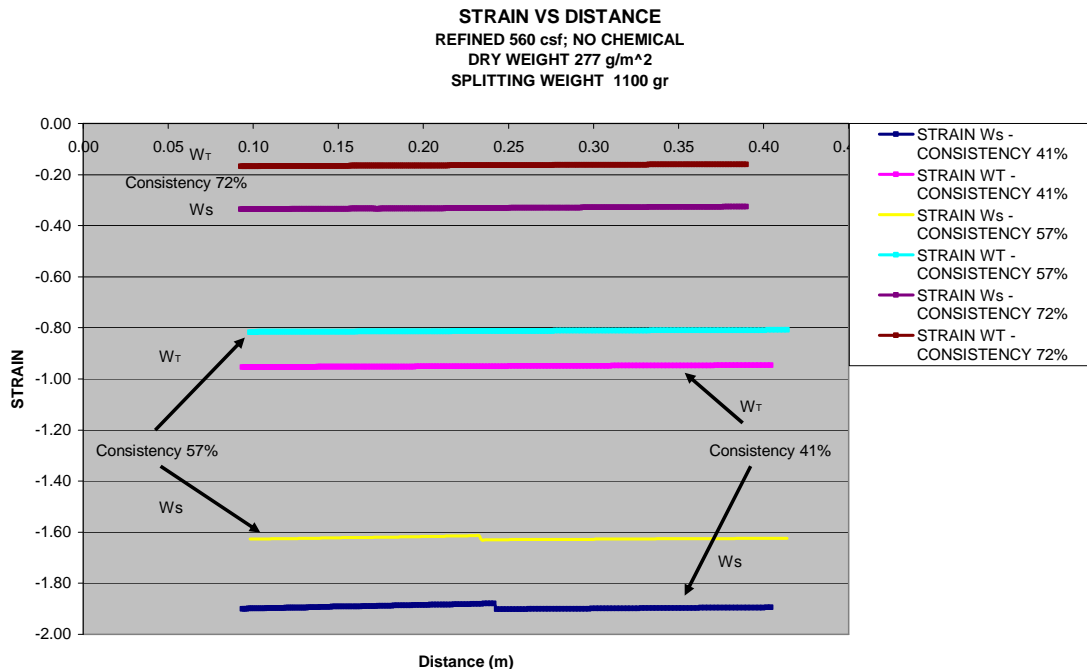


Figure 4.38 – Calculated Strain Curves (Solids 41, 57 and 72%)

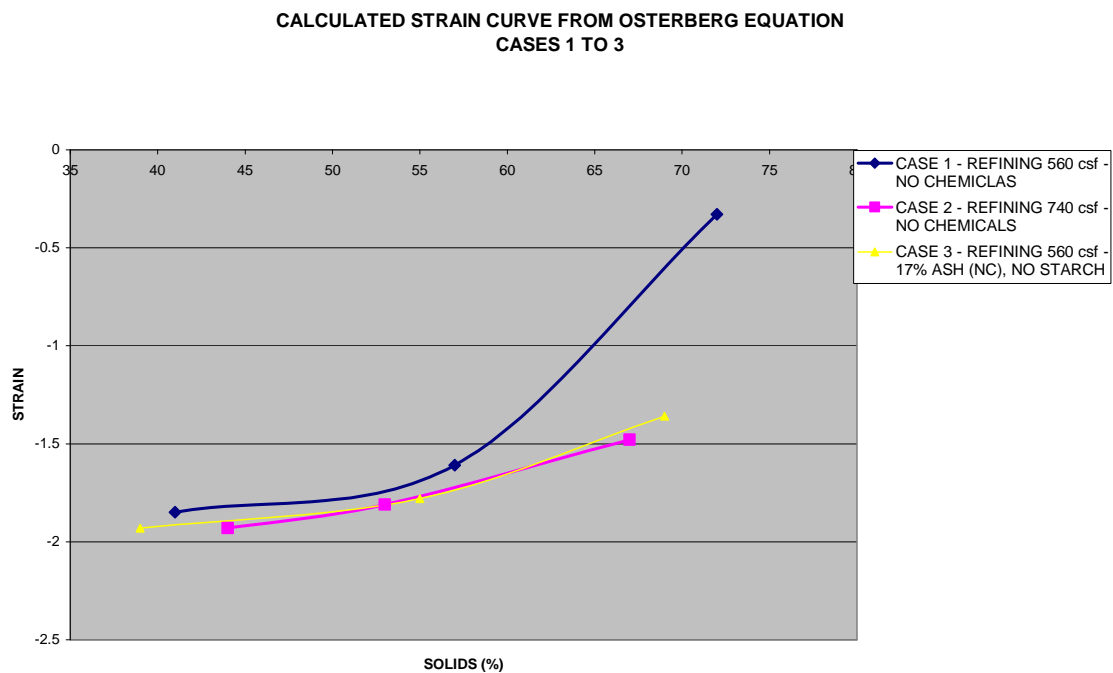


Figure 4.39 – Strain Vs Solids (Osterberg Formula for W_s)

Although strange, Osterberg gave some explanation for the negative strain values that occur for large take off angles.

1. The web shrinks by bending at the small bending angles with large take off angles
2. Before the separation the web tension is greater (on the point of separation) than after separation

Taylor (45) agrees with the first statement, he said that before the paper reaches the exact point of take off, it is already subjected to a bending strain tending to bend it upwards. Immediately (after) it has left the roll it is straightened out again (Figure 4.40). The difference between the first bend upwards and the second straightened bend is that, in the first, the paper is stuck to the roll so that the neutral axis is the actual interface between paper and roll. In the straightening bend, the neutral axis is in the mid surface between the two faces of the sheet. The first bend must shorten the mid surface, the second leaves it unchanged, at the end a reduction in the length is obtained.

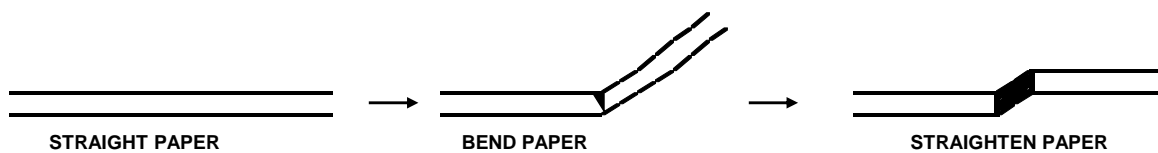


Figure 4.40 – Taylor Explanation of Negative Strain (45)

While the trends in strain calculated from W_S and W_T follow the trends in strain obtained from Instron tests, there is a discrepancy between the two which needs further investigation.

CHAPTER 5

CONCLUSIONS

The main objective of the thesis was to find a way to validate the results obtained for the cohesive energy of a paper web at various conditions usually encountered during the papermaking process. The most important characteristic of the apparatus is its ability to measure wet web properties at different solids starting at 20%, a value usually found after the couch roll and up to 95% corresponding to the solids of the web at the pope reel.

To validate the results obtained with the splitter apparatus, the variation of the two measuring energies, cohesive and bending, were compared with the variation of the tensile properties (obtained using an Instron tester) at different solids content. As expected the three kinds of energies behaves in a similar way allowing the identification of three main strength development stages during the production process. The first one between 20 and 55% corresponding to a low increase of the strength, the next one between 55 and 88% corresponding to a high increase of the strength and finally above 88% the growing process slows down. Below 20% solids it is not clear how the strength behaves and above 90% more test should be performed with the splitter test to explain the cohesive and bending abrupt reduction.

In addition to the evidence offered by the strength versus solids curves, the graph between the cohesive strength index and the tensile strength index at different solids content shows a linear relation between the indices, as stated by Page equation for wet webs. Although the relation for the different basis weights within the same case is not the same, the offset can be easily cancelled out by using a linear relation between the indices relation and the basis weight.

The final support is found when the strain is calculated using the formulas developed by Osterberg. In this case very reasonable values were obtained showing that the strain increases with the solids up to a level when they go down. The same effect is present in the strain obtained using the Instron test.

The work presented allows comparisons to be made for webs prepared using different mechanical and chemical treatments but following the same consolidation process. From this set of experiments several conclusions can be made:

1. The refining or mechanical treatment is a key factor to develop the web strength this is clear for all solids content
2. The clay addition reduces the strength of the paper, clearly seen for solids above 60%, below this point the reduction is small
3. When the ash content goes up from a critical value between 18 and 23%, the result is that the strength goes down to the values originally obtained with unrefined pulp

4. The webs produced using starch modified clay show a reduced strength loss when compared with normal clay. The effect can also be seen at solids below 60% although the effects vanish with the solids reduction. The reason for this is the presence of surfactants in the normal clay suspension that reduces the surface tension of the water
5. The starch addition increases the strength of the webs with ash. Also when starch was added as the only chemical, the strengths obtained were the higher ones through the entire solids levels

The splitter apparatus offers a new validated alternative to measure the web properties through the entire solids content found during the papermaking production. It also provides a reliable source to investigate how changes in the furnish, the mechanical and chemical treatments performed to the pulp suspension and how the consolidation process variations can affect the final performance of the web.

CHAPTER 6

RECOMENDATIONS

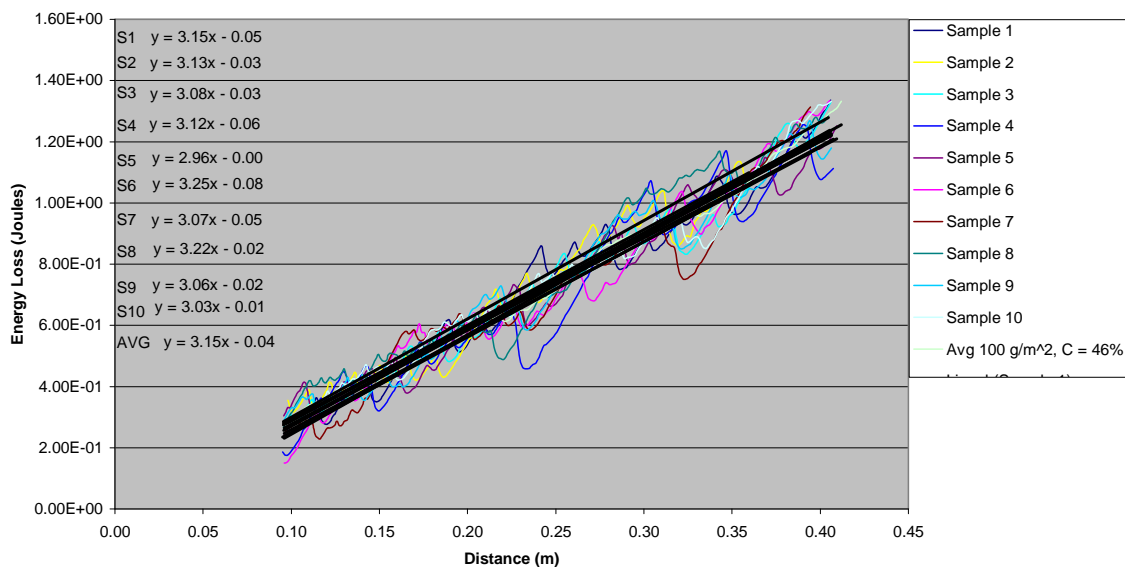
It is still necessary to investigate more the behavior of the web for solids greater than 88%. It is not completely clear with the strength drops in such a critical way above this value. One guess is that when testing the strips with high solids, the splitting weight that was enough to create a crack propagated at a constant positive acceleration for weaker webs, is not enough to obtain a positive acceleration with this new condition. This was observed in several samples, when the velocity goes down some strange low splitting results were obtained. To be safe it is necessary to choose the splitting weight in such a way that for the higher energy requirement the acceleration obtained will be at least 1.5 m/s^2 . The problem with choosing an excessive high splitting weight is that the low solids weak web can break during the assembly of the test. Also it is better to make all the test using the same splitting weights because doing so the effect of friction is diminished.

More testing should be done to explain the different behavior of the cohesive and tensile strength indices when comparing different basis weights. The results showed that the relation between the indices is dependent on the basis weight. This should not be the case for webs formed following the same procedures with its only difference being the basis weight. It would also be helpful to pursue a theoretical investigation of the results.

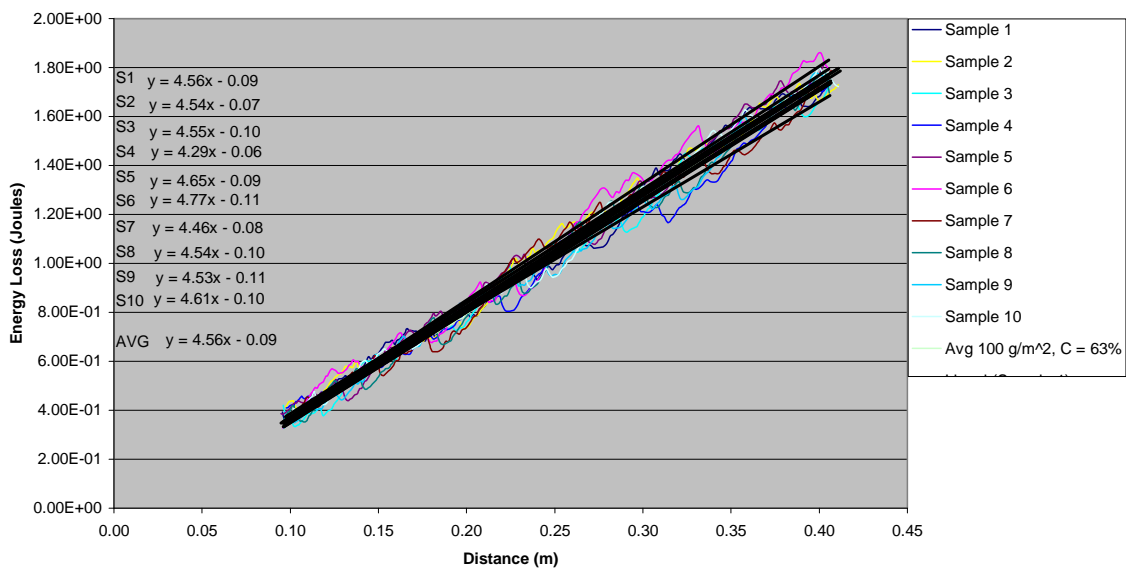
**APPENDIX A.1: APPARATUS ENERGY LOSS VS DISTANCE –
CASE 1 TO 3**

Case 1: Refining 560 C.S.F.; No Chemicals; Basis Weight 101 g/m²

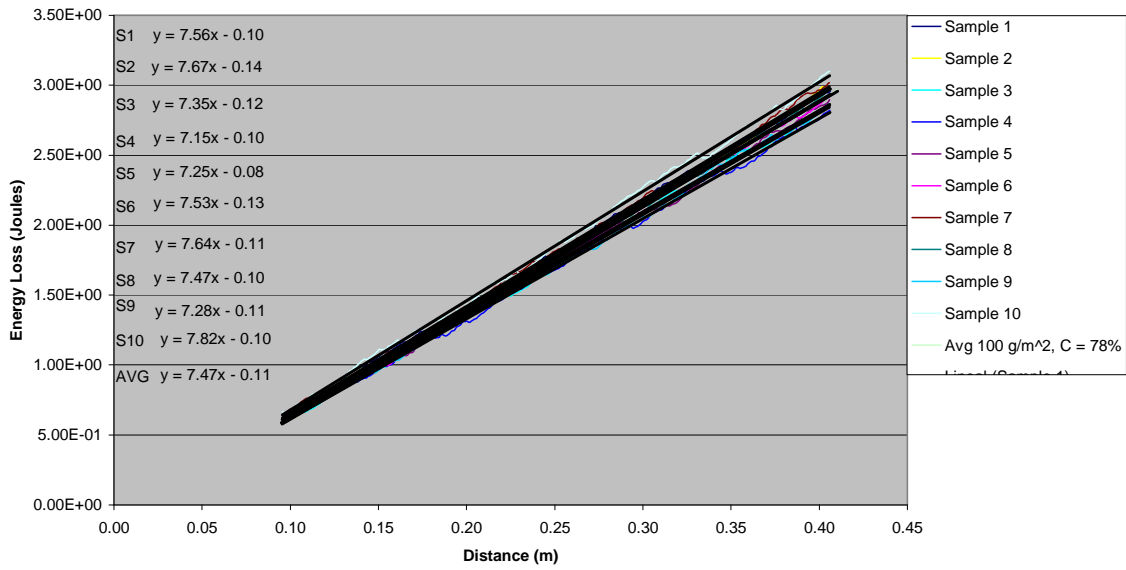
REFINED 560 csf - 100 g/m²
 CONSISTENCY = 46 %
 SPLITTING WEIGHT 1100 gr



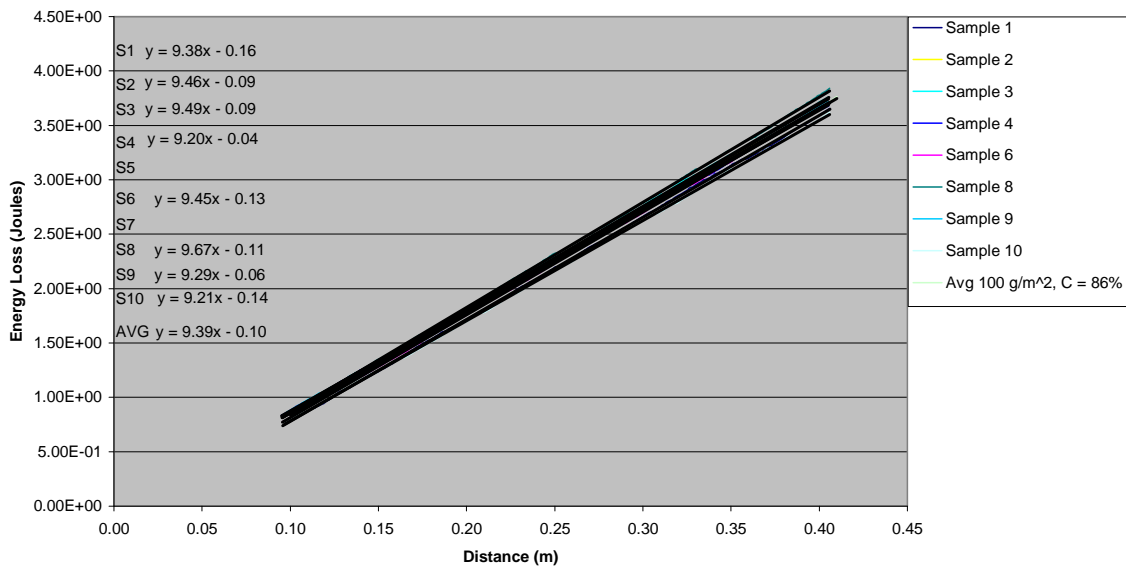
REFINED 560 csf - 100 g/m²
 CONSISTENCY = 63 %
 SPLITTING WEIGHT 1100 gr



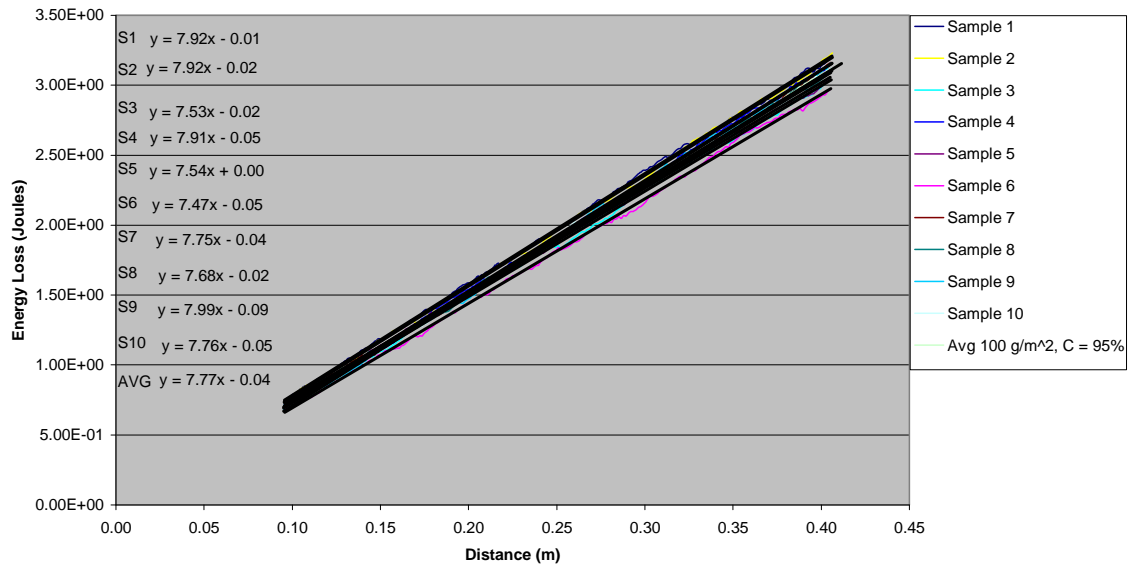
REFINED 560 csf - 100 g/m²
 CONSISTENCY = 78 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf - 100 g/m²
 CONSISTENCY = 86 %
 SPLITTING WEIGHT 1100 gr

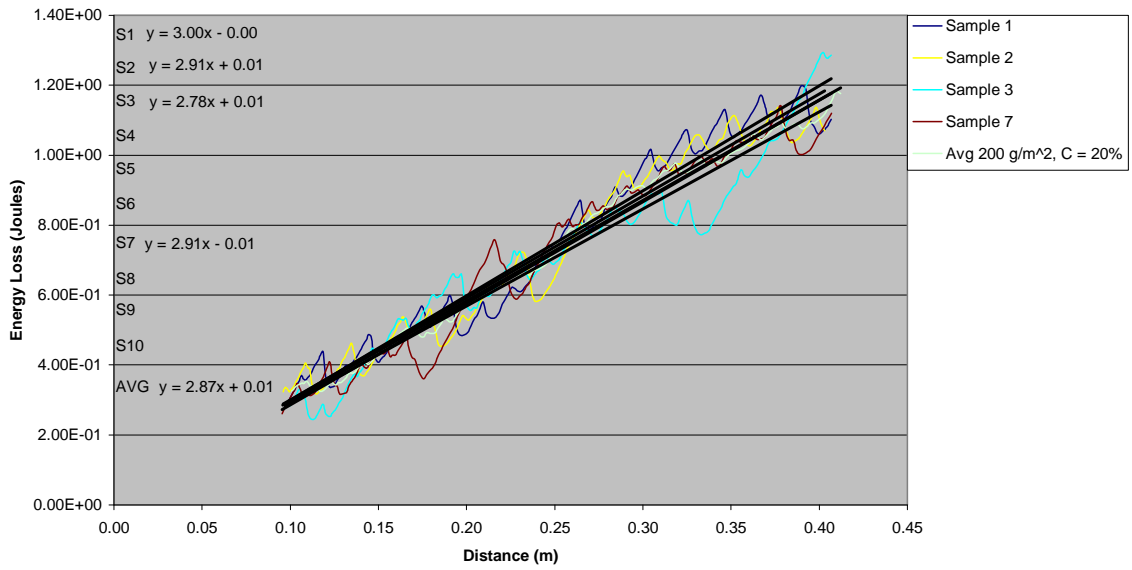


REFINED 560 csf - 100 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

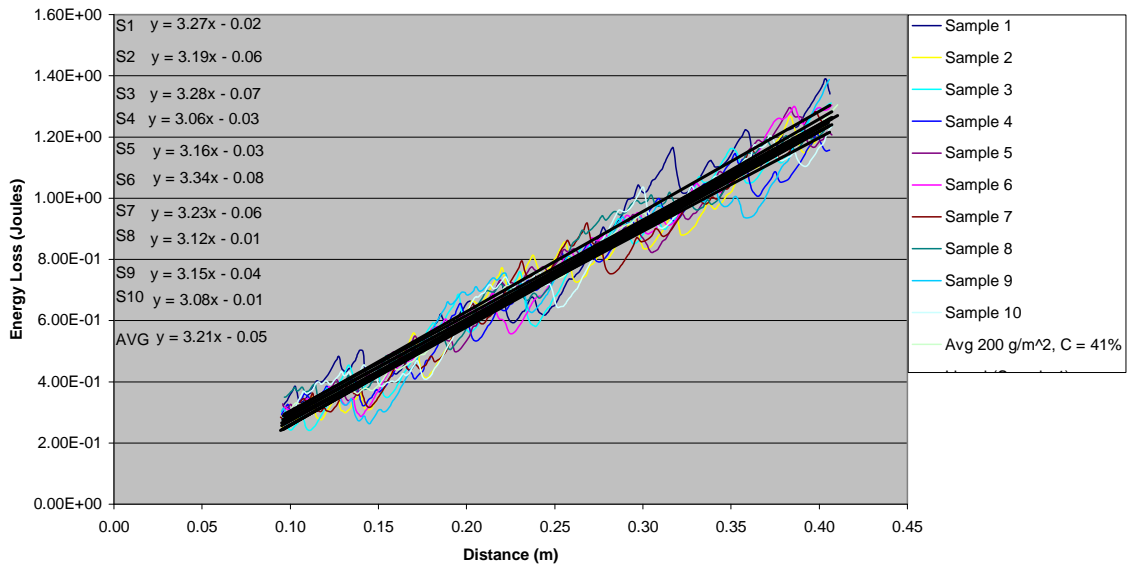


Case 1: Refining 560 C.S.F.; No Chemicals; Basis Weight 191 g/m²

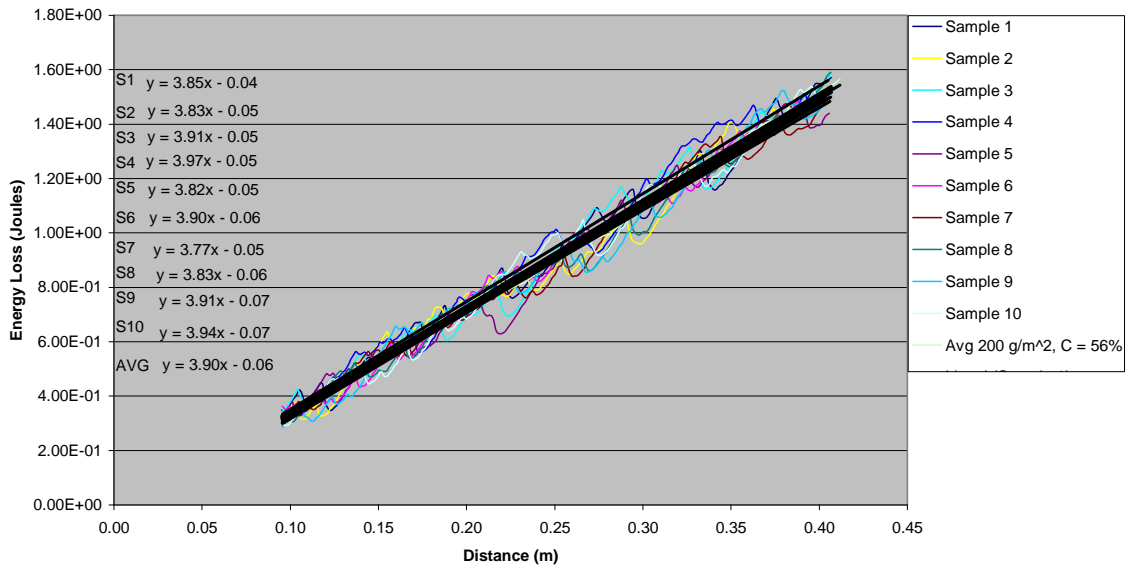
REFINED 560 csf - 191 g/m²
 CONSISTENCY = 20 %
 SPLITTING WEIGHT 1100 gr



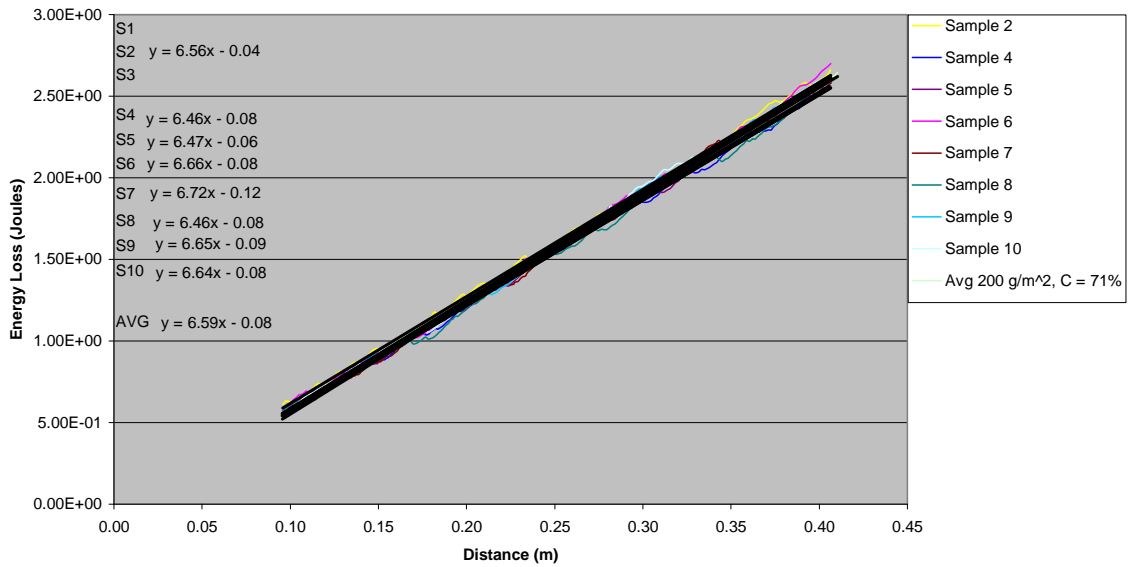
REFINED 560 csf - 191 g/m²
 CONSISTENCY = 41 %
 SPLITTING WEIGHT 1100 gr



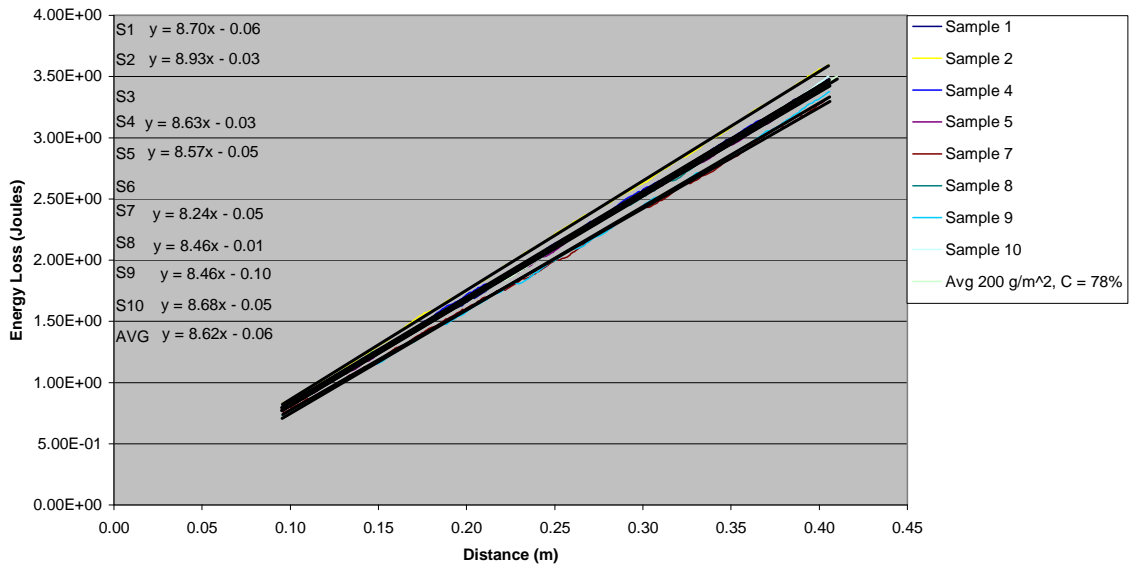
REFINED 560 csf - 191 g/m²
 CONSISTENCY = 56 %
 SPLITTING WEIGHT 1100 gr



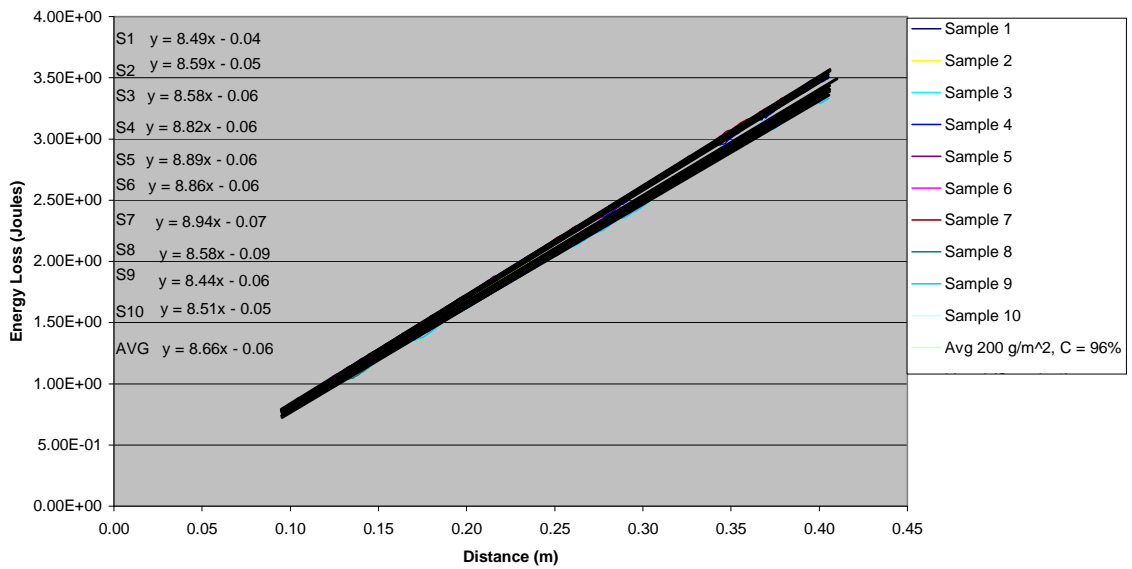
REFINED 560 csf - 191 g/m²
 CONSISTENCY = 71 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf - 191 g/m²
 CONSISTENCY = 78 %
 SPLITTING WEIGHT 1100 gr

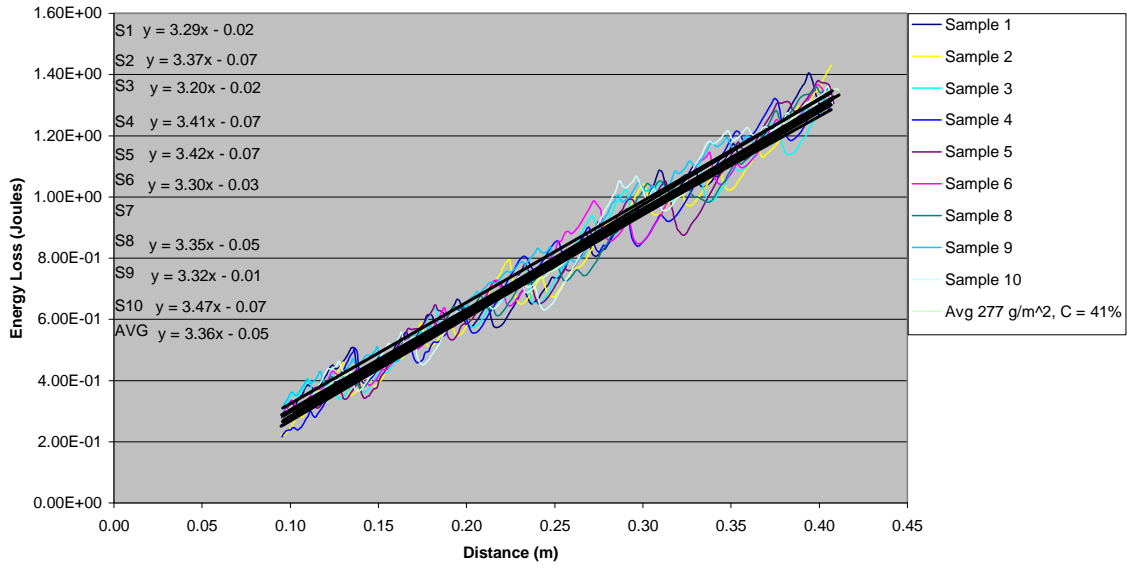


REFINED 560 csf - 191 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1100 gr

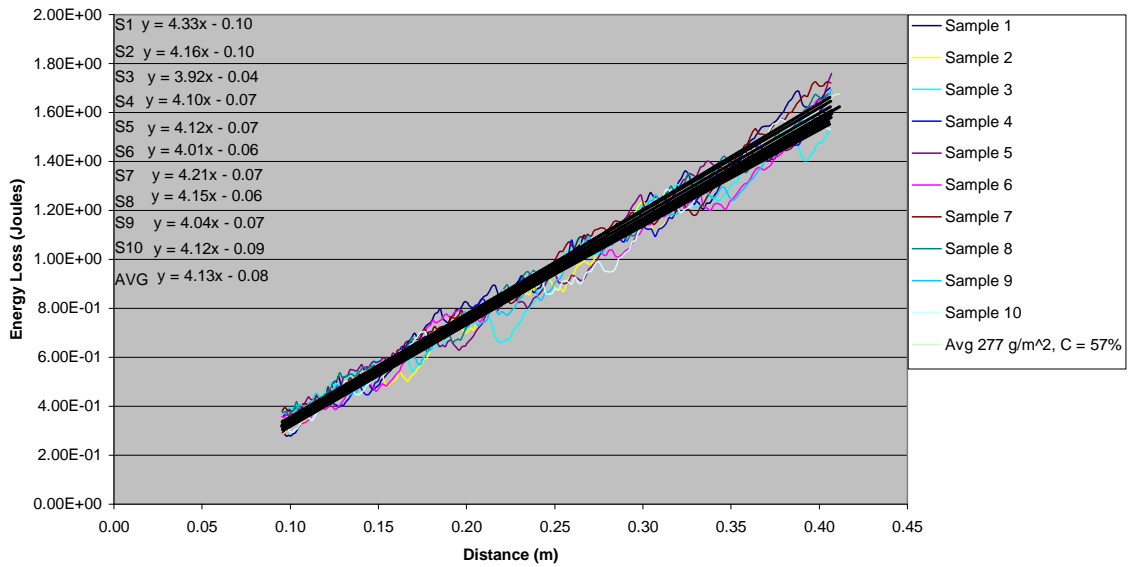


Case 1: Refining 560 C.S.F.; No Chemicals; Basis Weight 277 g/m²

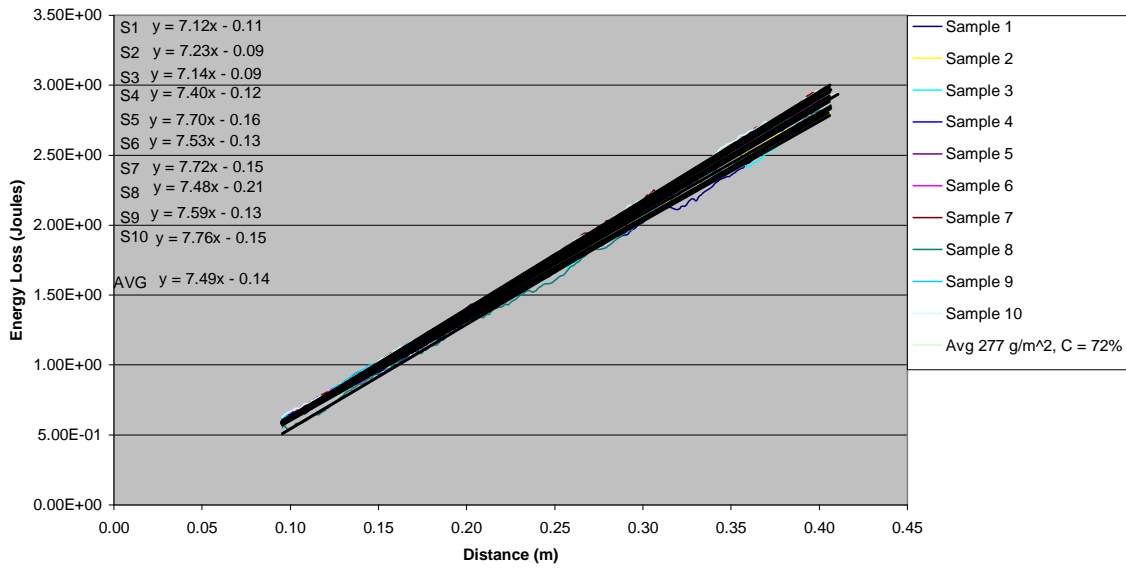
REFINED 560 csf - 277 g/m²
 CONSISTENCY = 41 %
 SPLITTING WEIGHT 1100 gr



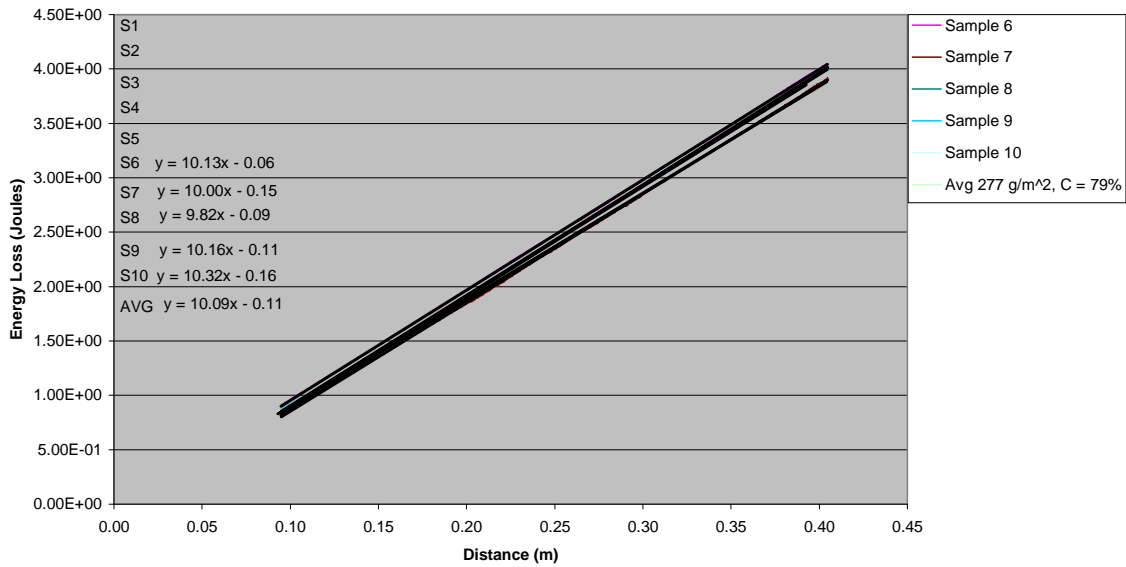
REFINED 560 csf - 277 g/m²
 CONSISTENCY = 57 %
 SPLITTING WEIGHT 1100 gr



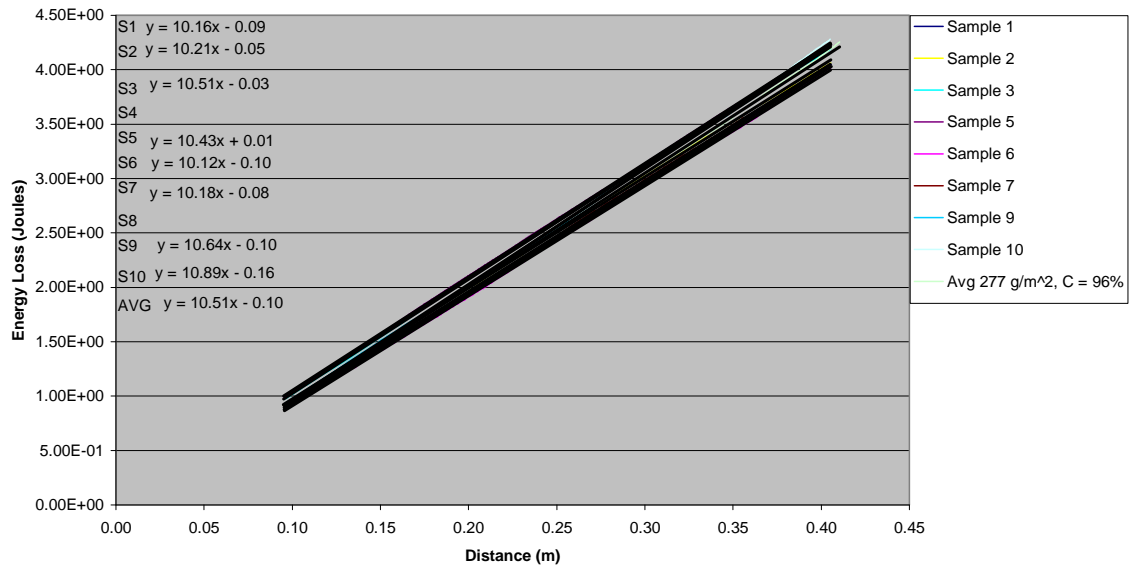
REFINED 560 csf - 277 g/m²
 CONSISTENCY = 72 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf - 277 g/m²
 CONSISTENCY = 79 %
 SPLITTING WEIGHT 1100 gr

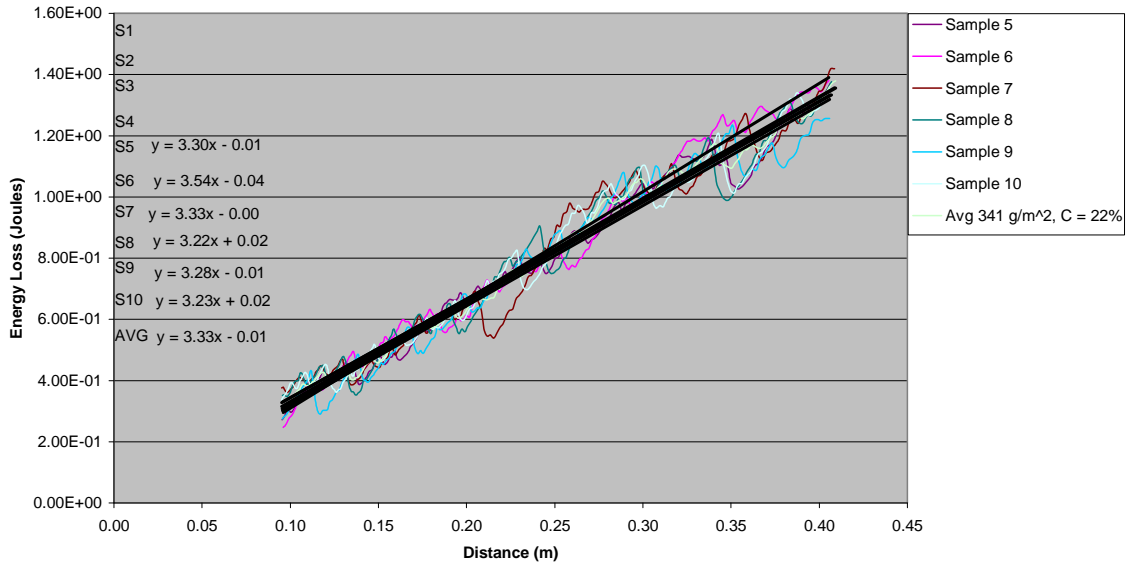


REFINED 560 csf - 277 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1100 gr

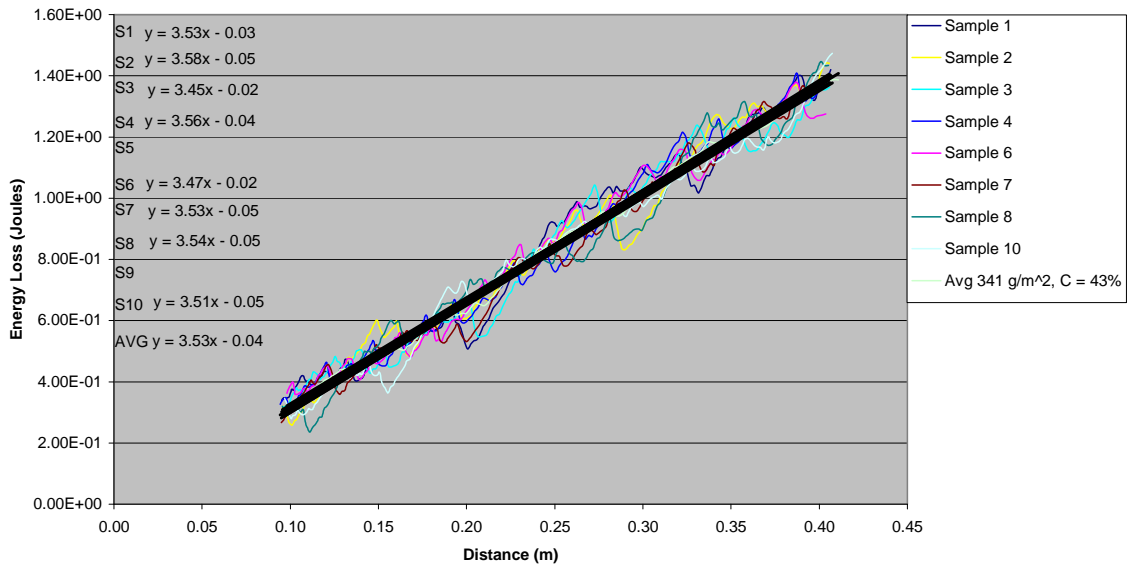


Case 1: Refining 560 C.S.F.; No Chemicals; Basis Weight 341 g/m²

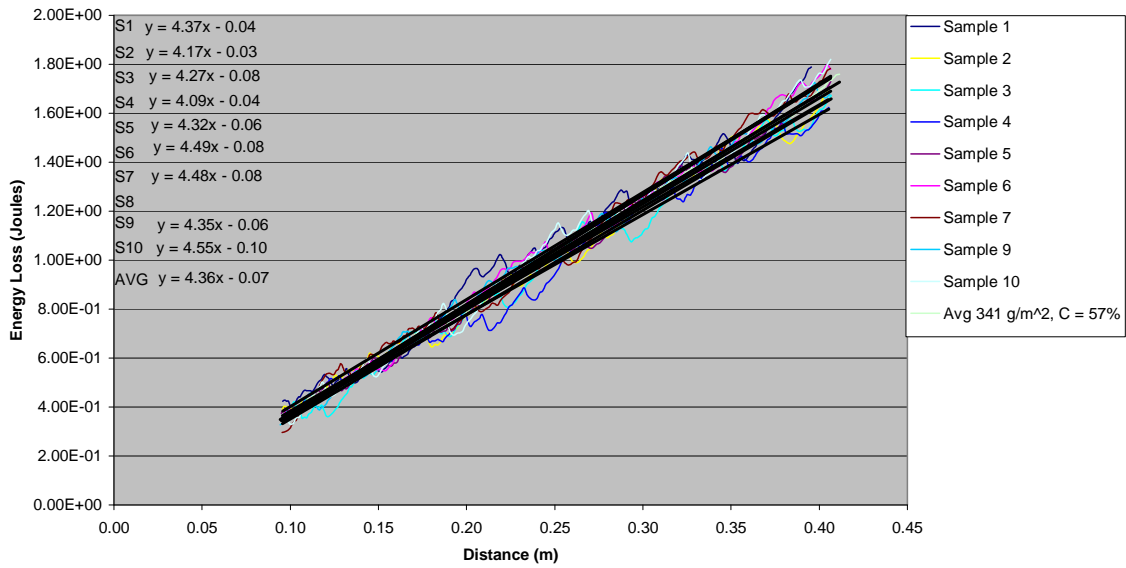
REFINED 560 csf - 341 g/m²
 CONSISTENCY = 22 %
 SPLITTING WEIGHT 1100 gr



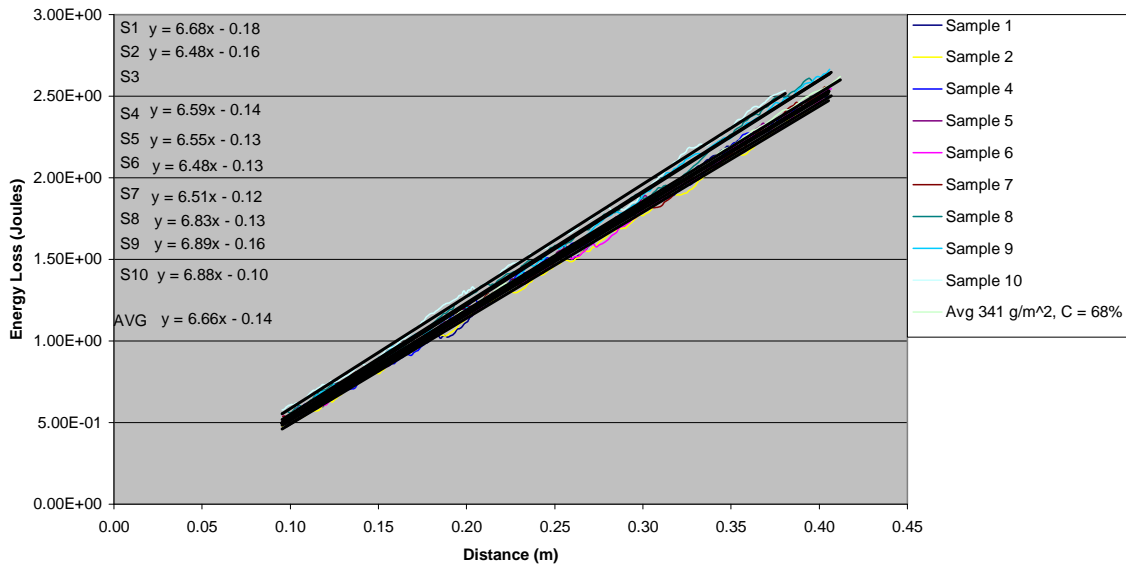
REFINED 560 csf - 341 g/m²
 CONSISTENCY = 43 %
 SPLITTING WEIGHT 1100 gr



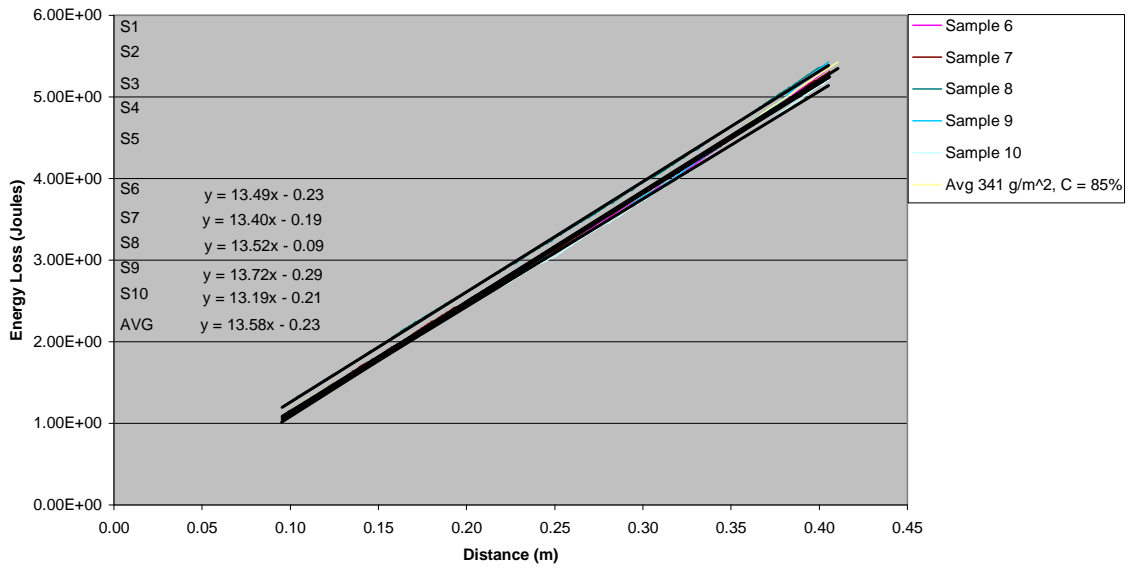
REFINED 560 csf - 341 g/m²
 CONSISTENCY = 57 %
 SPLITTING WEIGHT 1100 gr



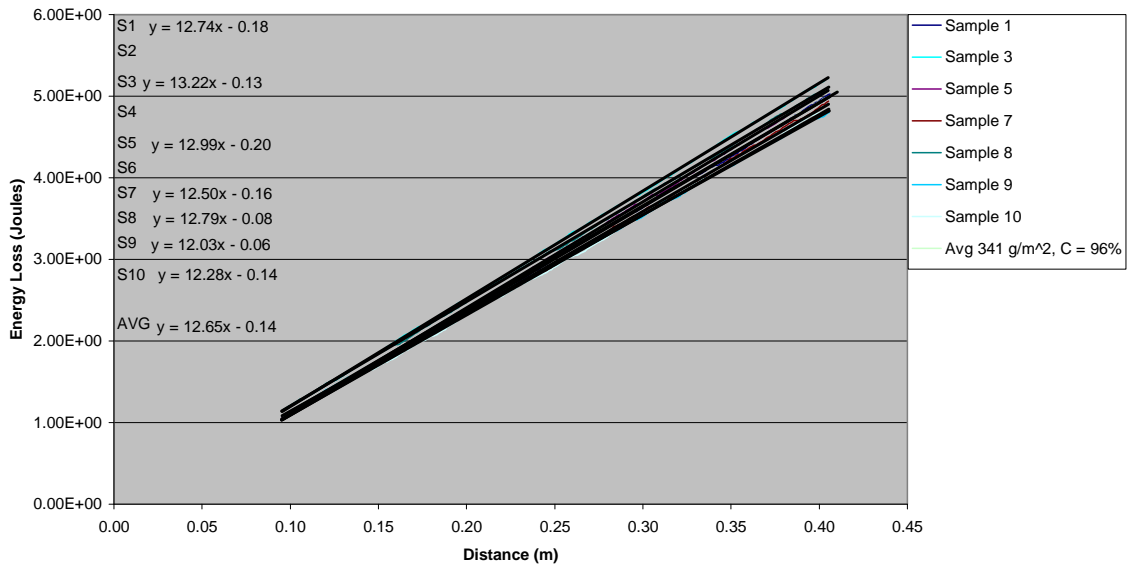
REFINED 560 csf - 341 g/m²
 CONSISTENCY = 68 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf - 341 g/m²
 CONSISTENCY = 85 %
 SPLITTING WEIGHT 1540 gr

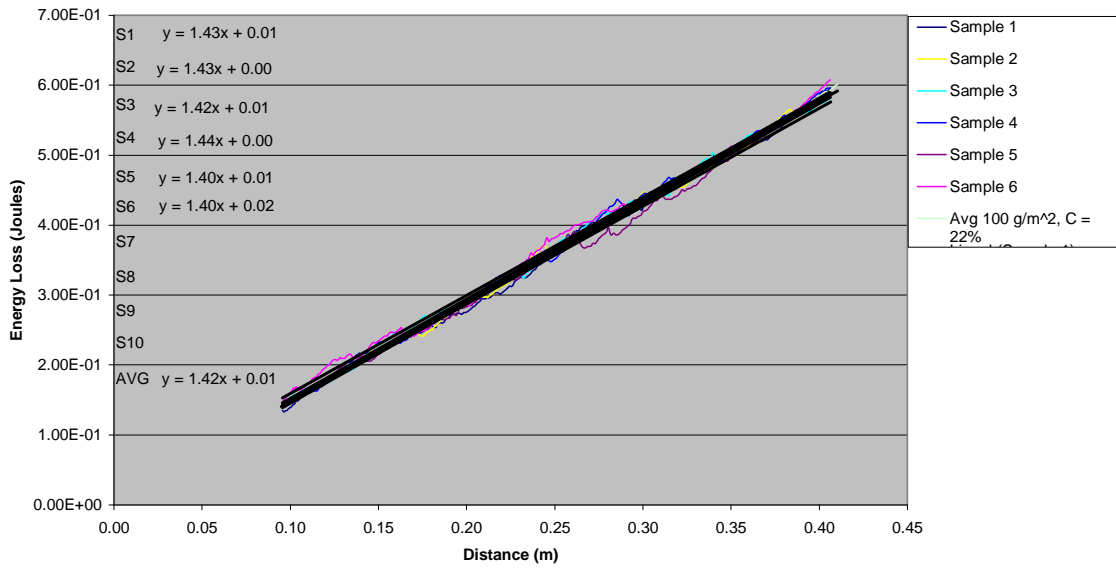


REFINED 560 csf - 341 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1540 gr

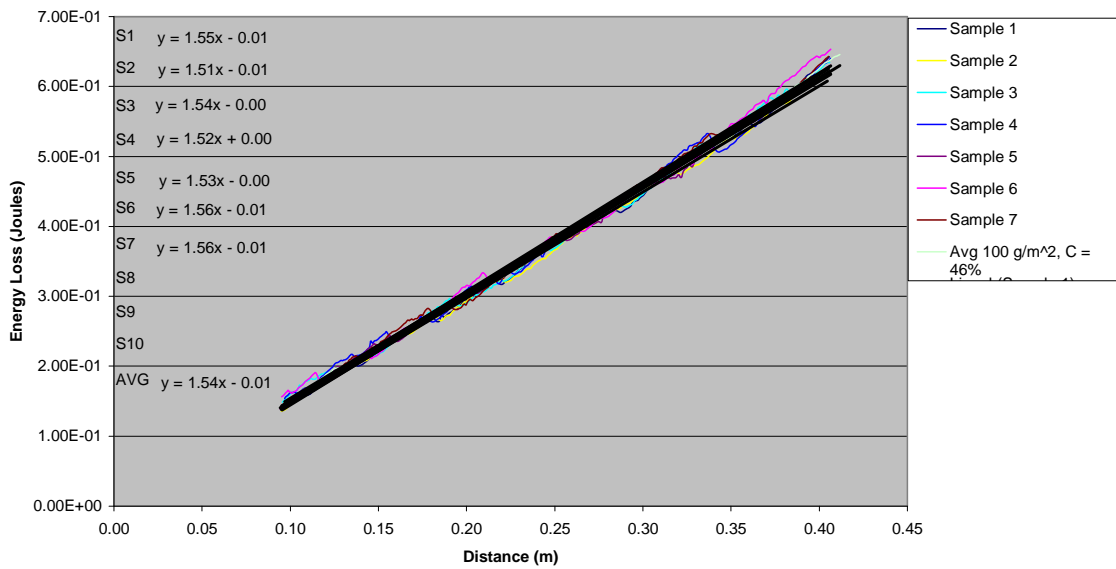


Case 2: Refining 740 C.S.F.; No Chemicals; Basis Weight 99 g/m²

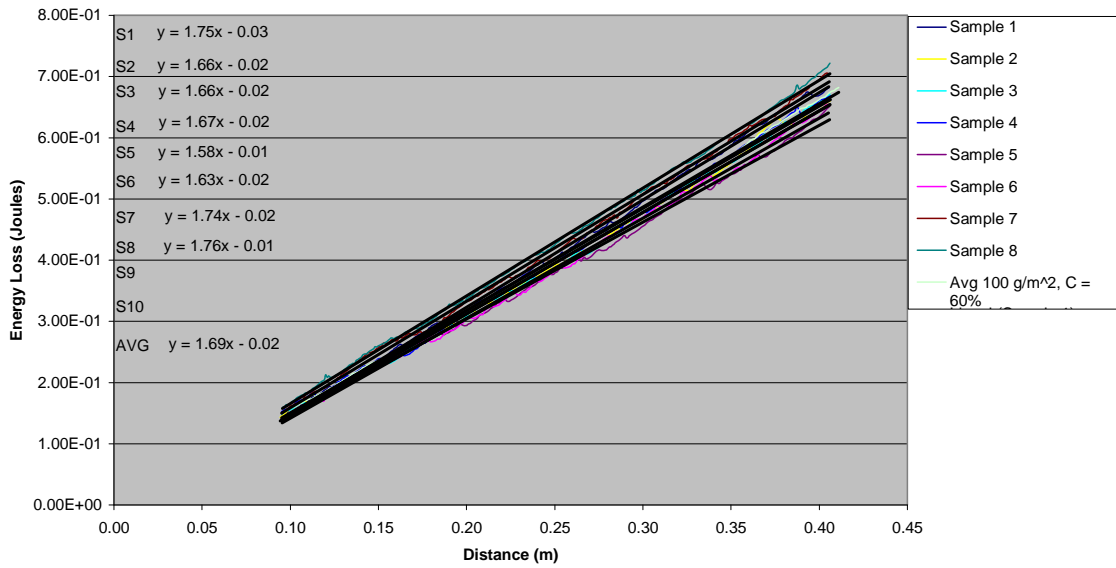
REFINED 770 csf - 100 g/m²
 CONSISTENCY = 22 %
 SPLITTING WEIGHT 250 gr



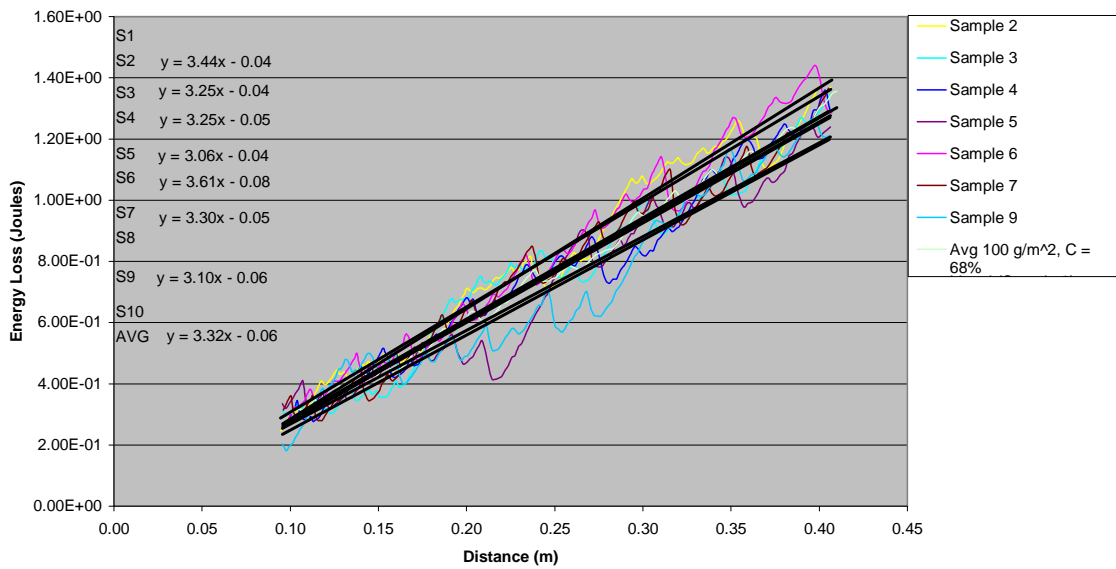
REFINED 770 csf - 100 g/m²
 CONSISTENCY = 46 %
 SPLITTING WEIGHT 250 gr



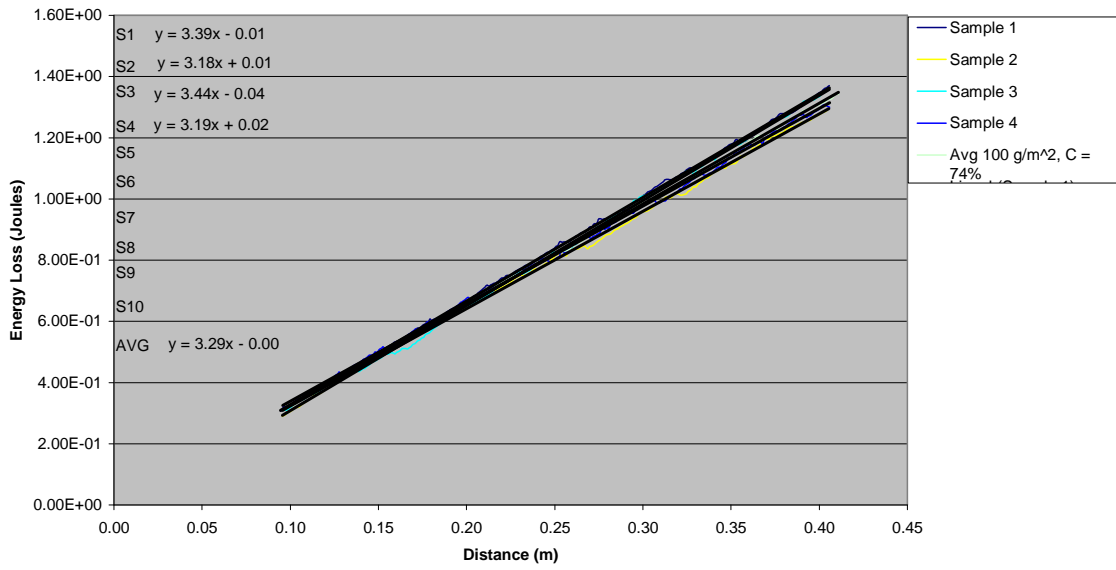
REFINED 770 csf - 100 g/m²
 CONSISTENCY = 60 %
 SPLITTING WEIGHT 250 gr



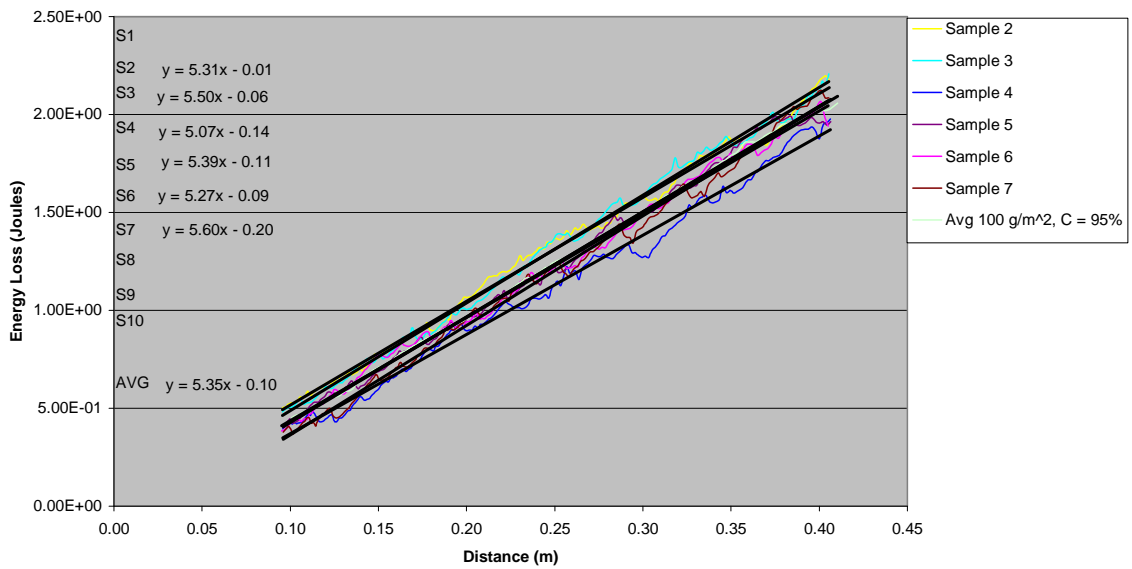
REFINED 770 csf - 100 g/m²
 CONSISTENCY = 68 %
 SPLITTING WEIGHT 1100 gr



REFINED 770 csf - 100 g/m²
 CONSISTENCY = 74 %
 SPLITTING WEIGHT 466 gr

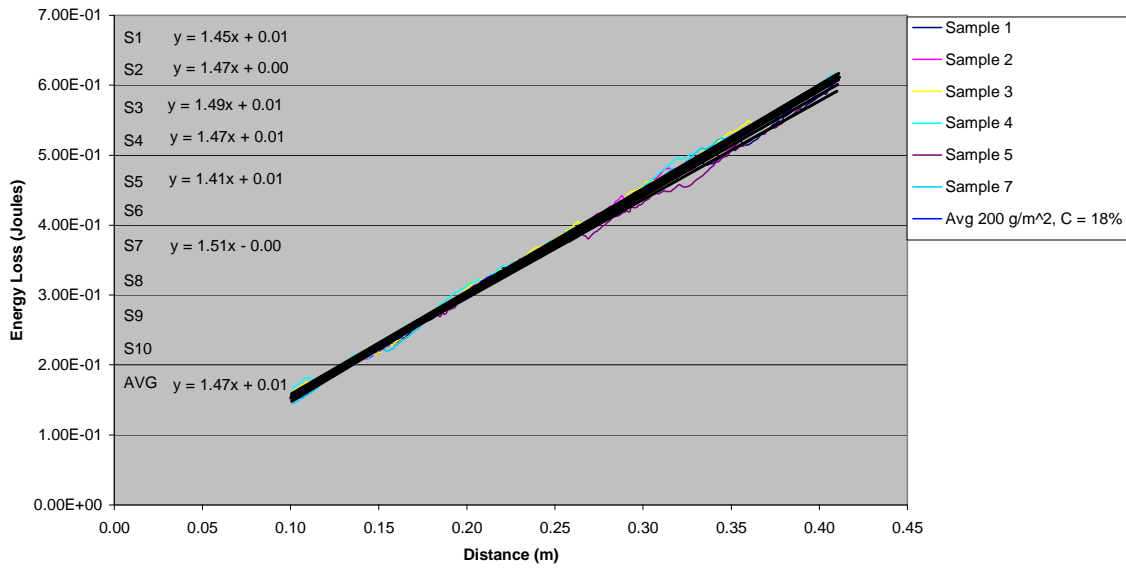


REFINED 770 csf - 100 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

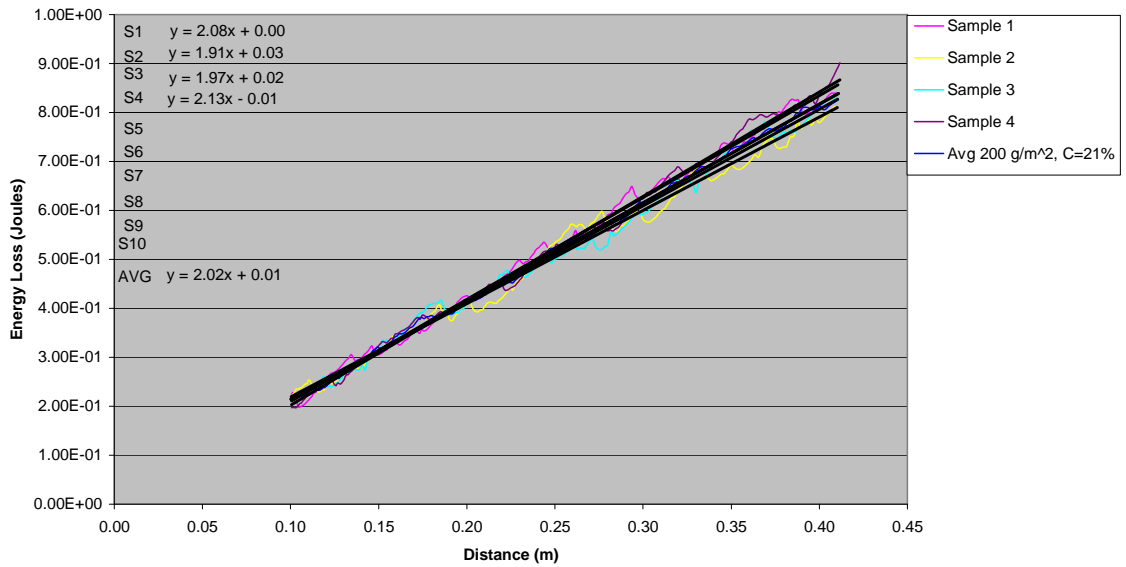


Case 2: Refining 740 C.S.F.; No Chemicals; Basis Weight 199 g/m²

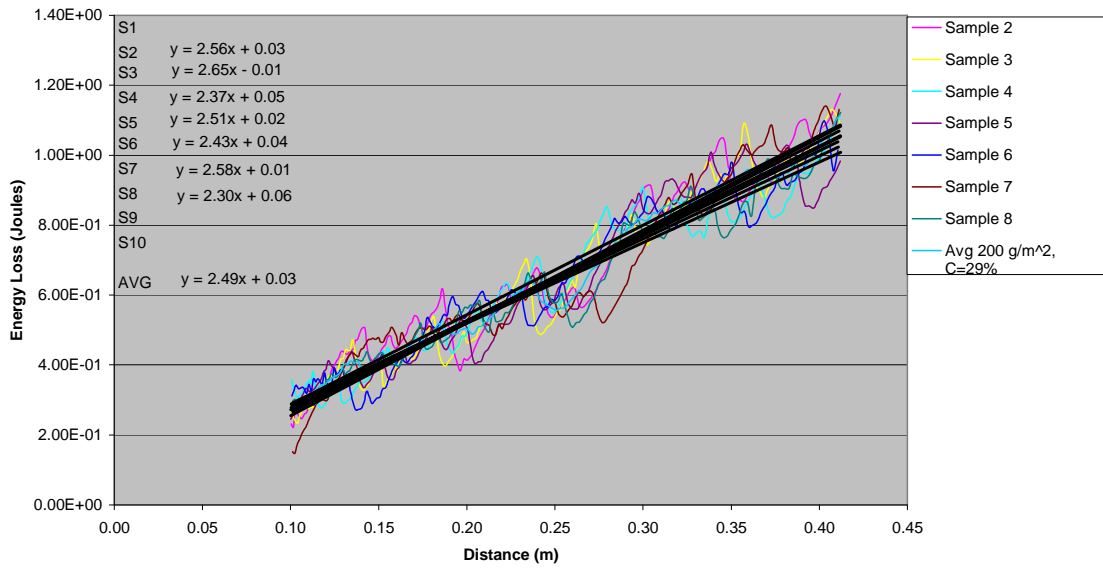
REFINED 770 csf - 200 g/m²
 CONSISTENCY = 18 %
 SPLITTING WEIGHT 250 gr



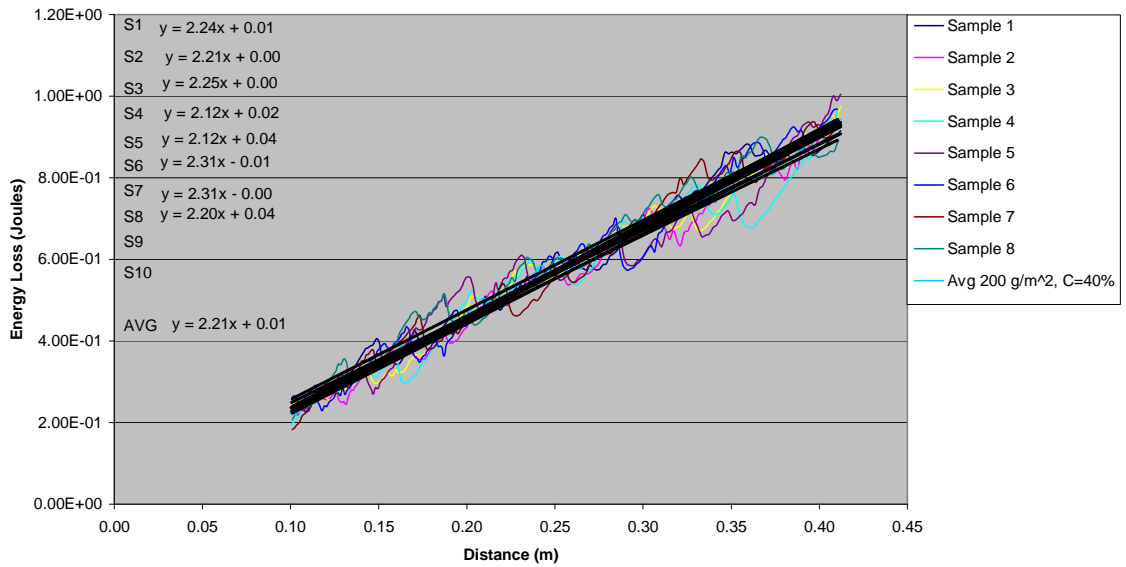
REFINED 770 csf - 200 g/m²
 CONSISTENCY = 21 %
 SPLITTING WEIGHT 466 gr



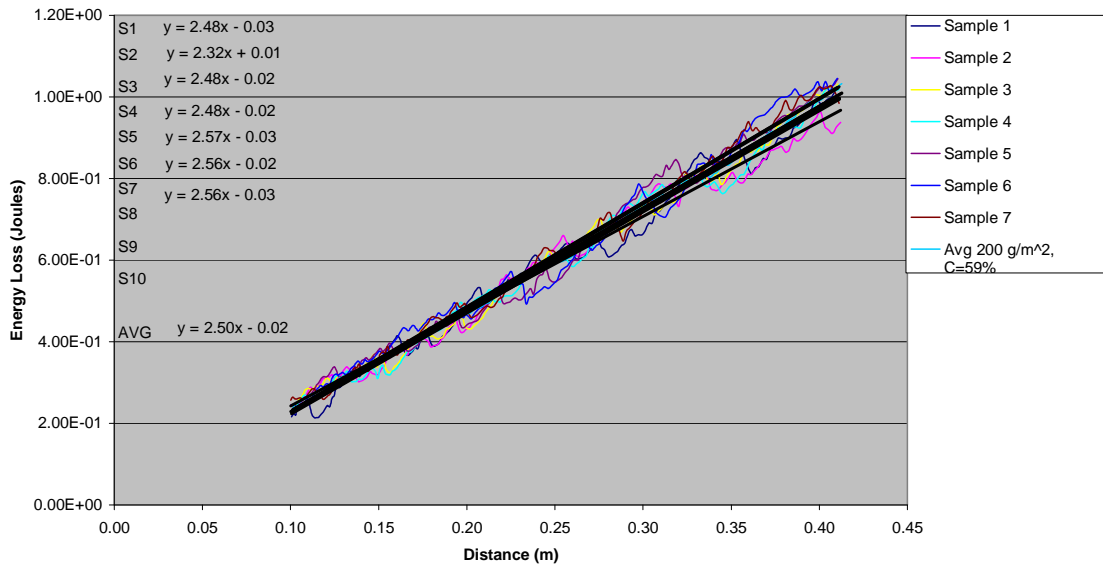
REFINED 770 csf - 200 g/m²
 CONSISTENCY = 29 %
 SPLITTING WEIGHT 1100 gr



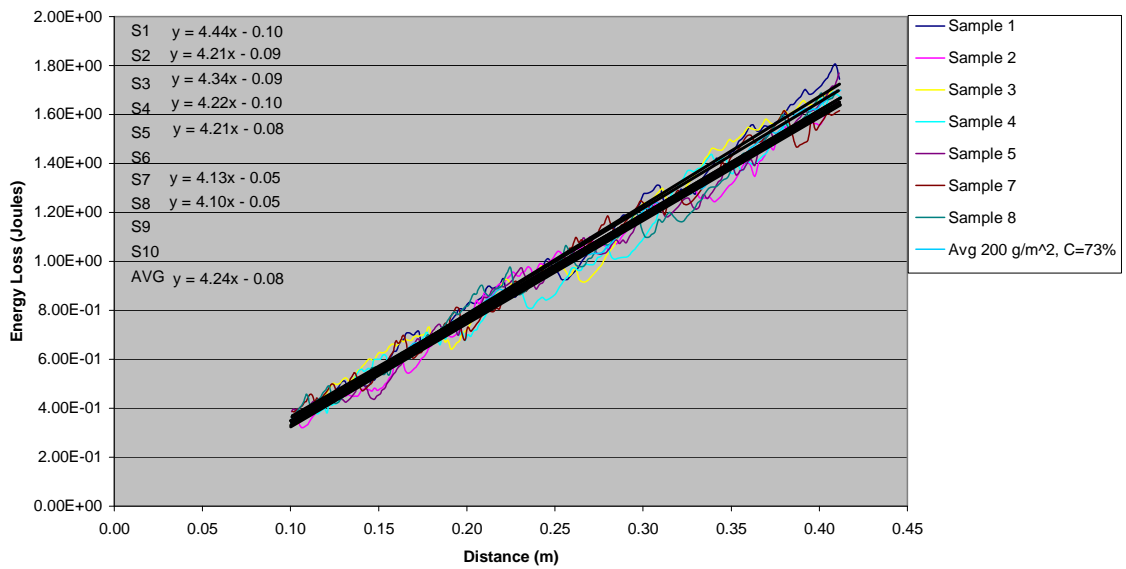
REFINED 770 csf - 200 g/m²
 CONSISTENCY = 40 %
 SPLITTING WEIGHT 660 gr



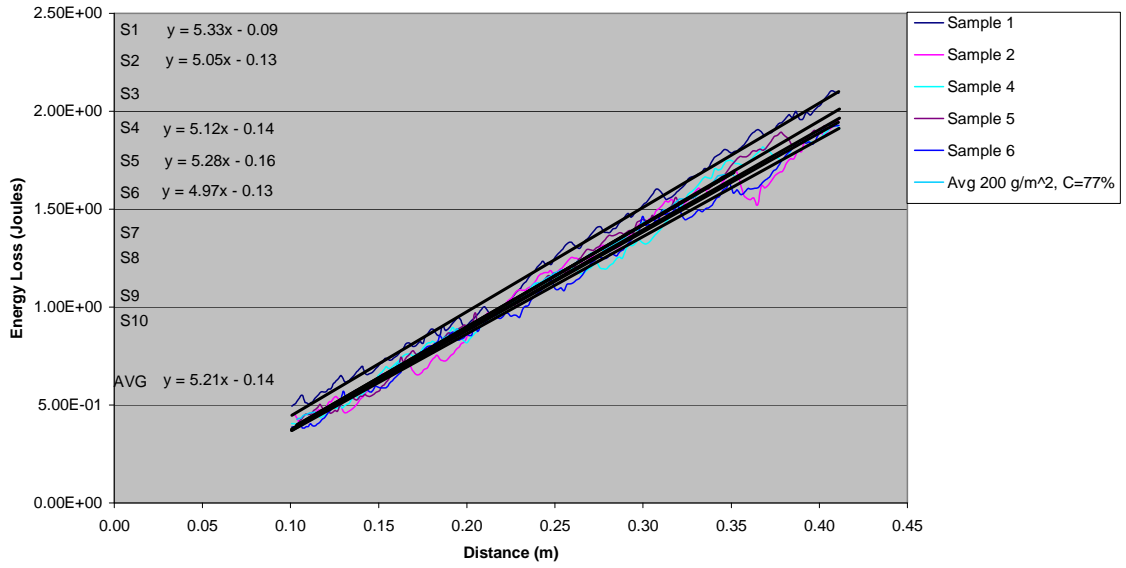
REFINED 770 csf - 200 g/m²
 CONSISTENCY = 59 %
 SPLITTING WEIGHT 660 gr



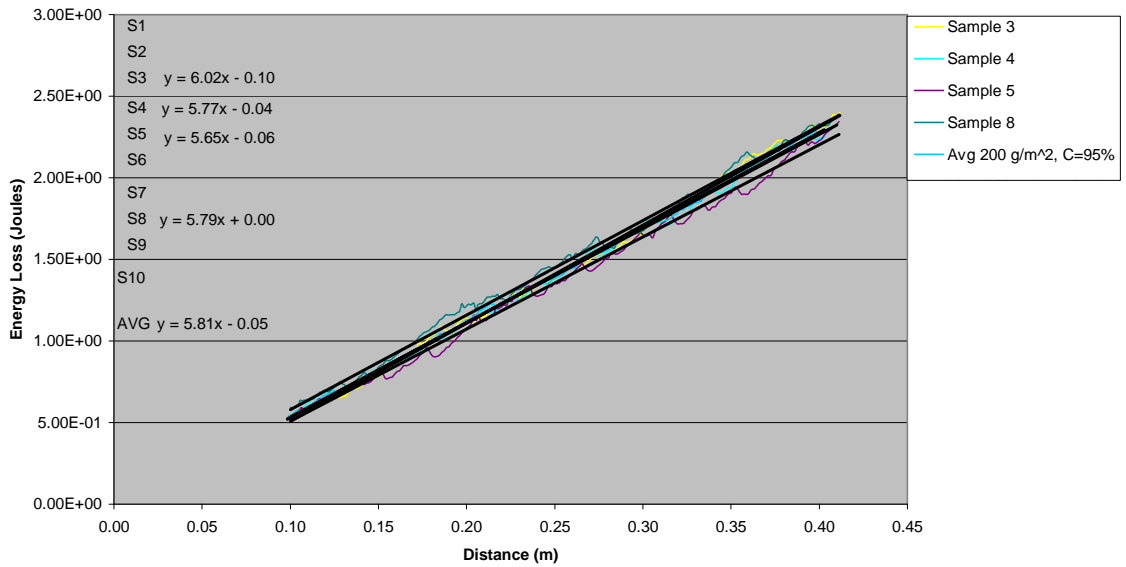
REFINED 770 csf - 200 g/m²
 CONSISTENCY = 73 %
 SPLITTING WEIGHT 1100 gr



REFINED 770 csf - 200 g/m²
 CONSISTENCY = 77 %
 SPLITTING WEIGHT 1100 gr

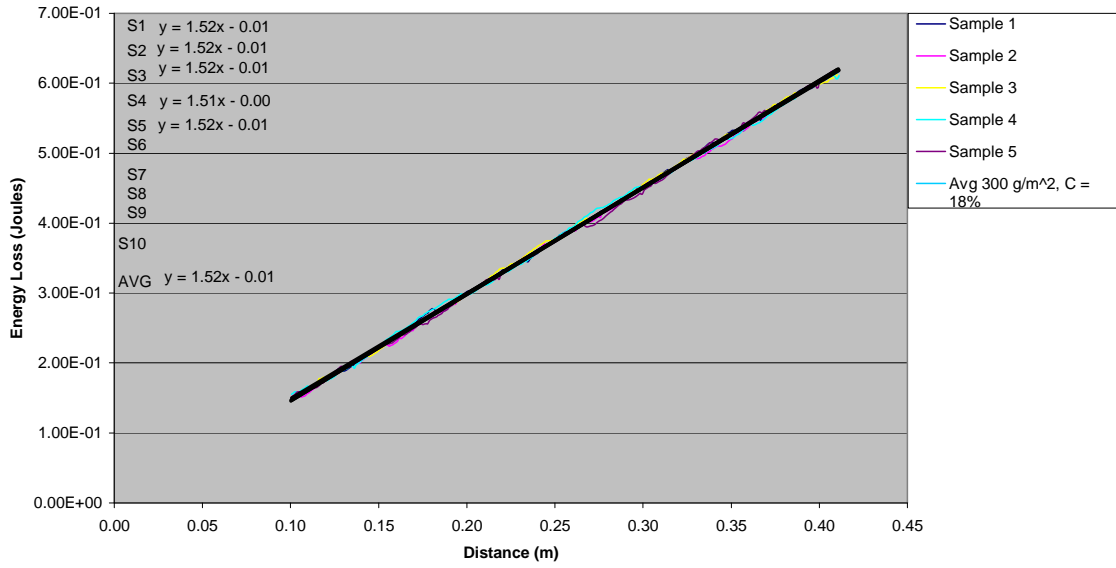


REFINED 770 csf - 200 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

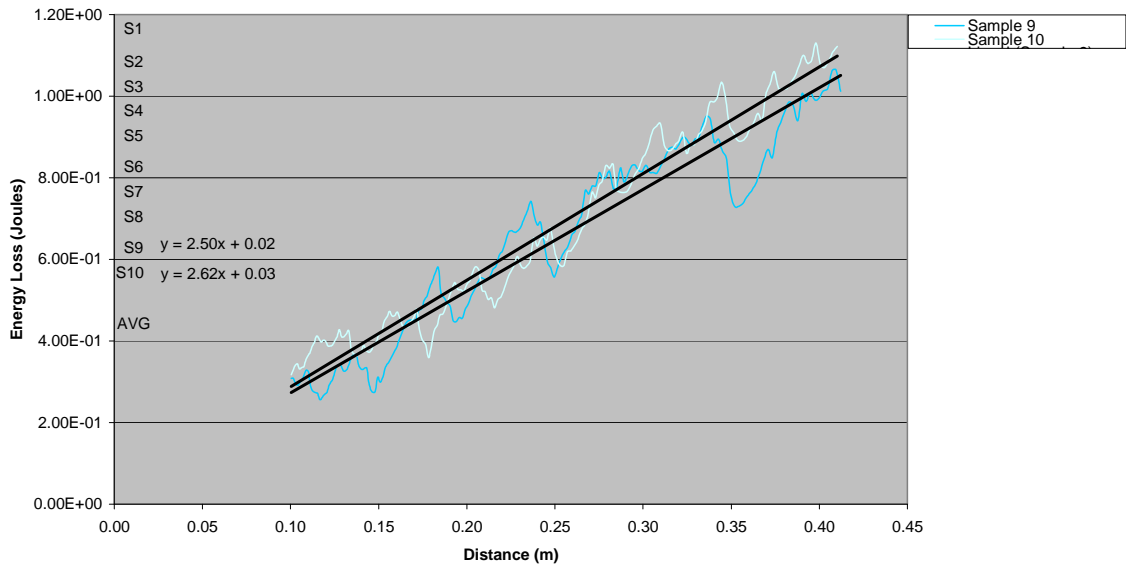


Case 2: Refining 740 C.S.F.; No Chemicals; Basis Weight 302 g/m²

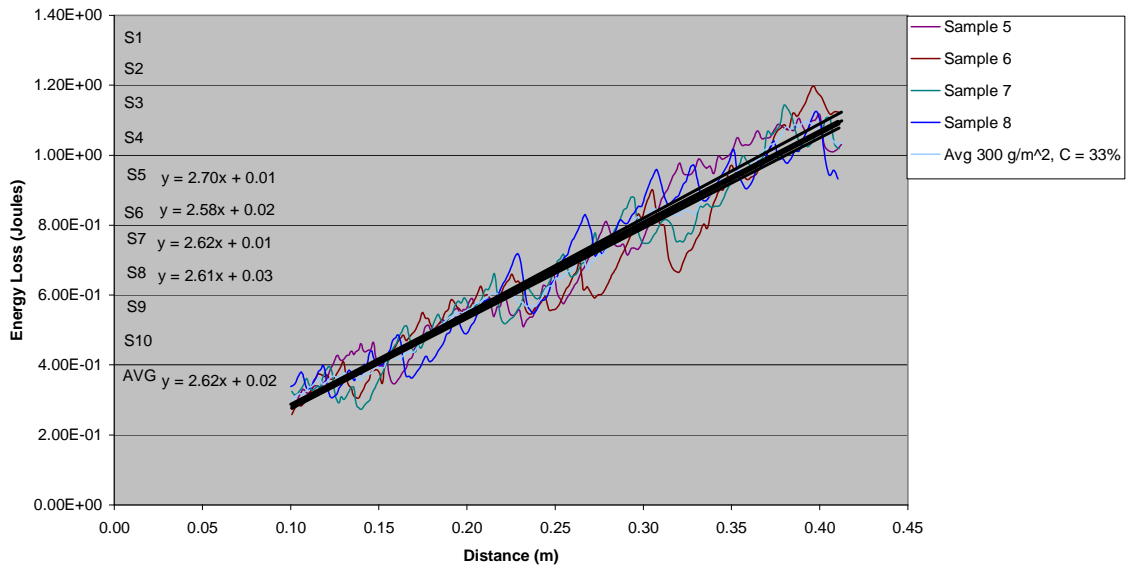
REFINED 770 csf - 300 g/m²
 CONSISTENCY = 18 %
 SPLITTING WEIGHT 250 gr



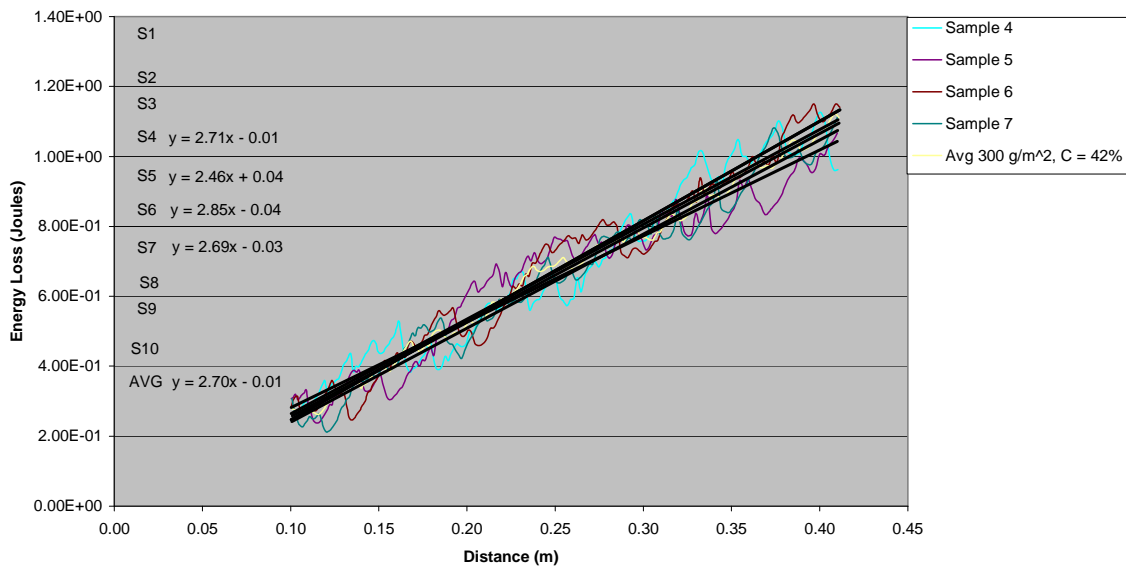
REFINED 770 csf - 300 g/m²
 CONSISTENCY = 24 %
 SPLITTING WEIGHT 1100 gr



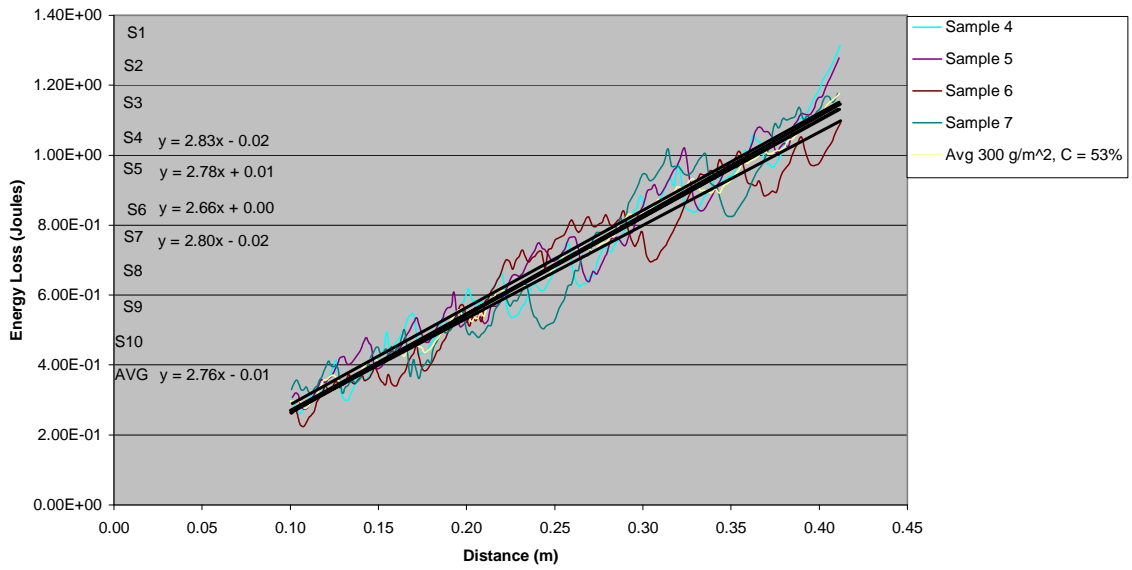
REFINED 770 csf - 300 g/m²
 CONSISTENCY = 33 %
 SPLITTING WEIGHT 1100 gr



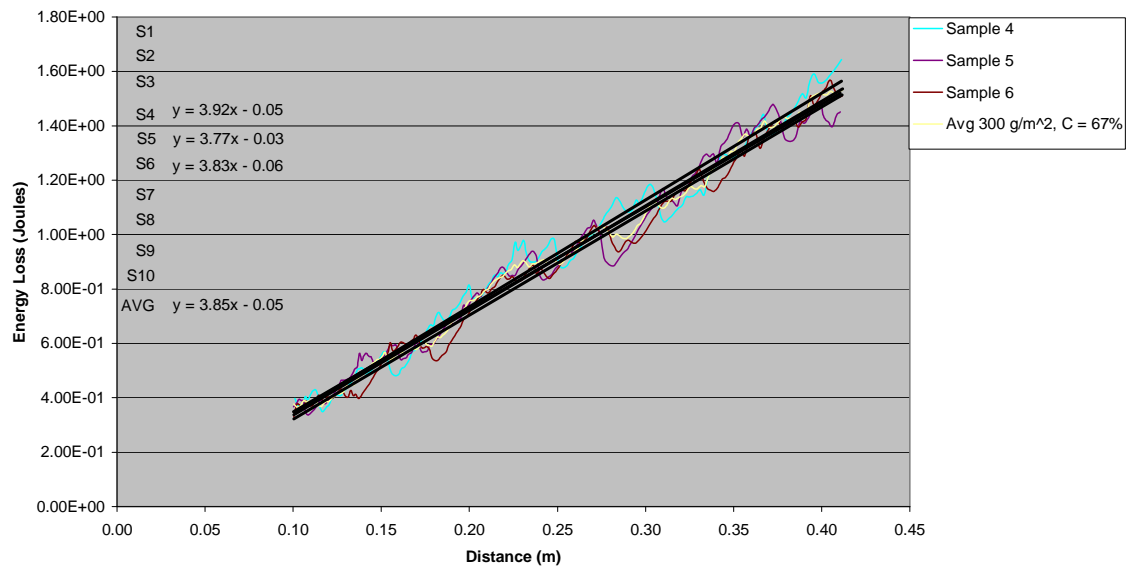
REFINED 770 csf - 300 g/m²
 CONSISTENCY = 42 %
 SPLITTING WEIGHT 1100 gr



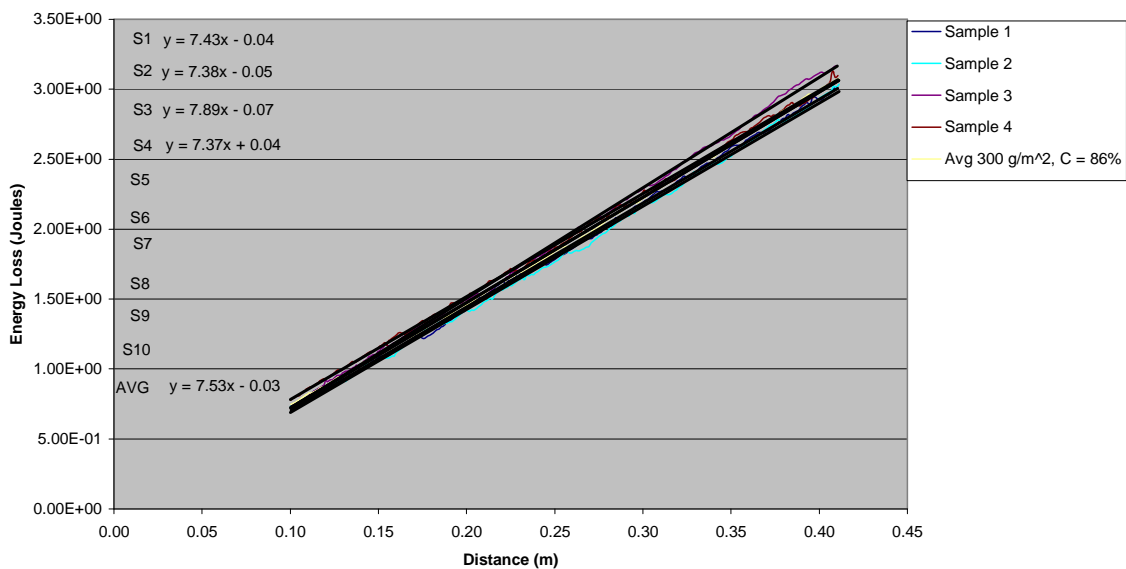
REFINED 770 csf - 300 g/m²
 CONSISTENCY = 53 %
 SPLITTING WEIGHT 1100 gr



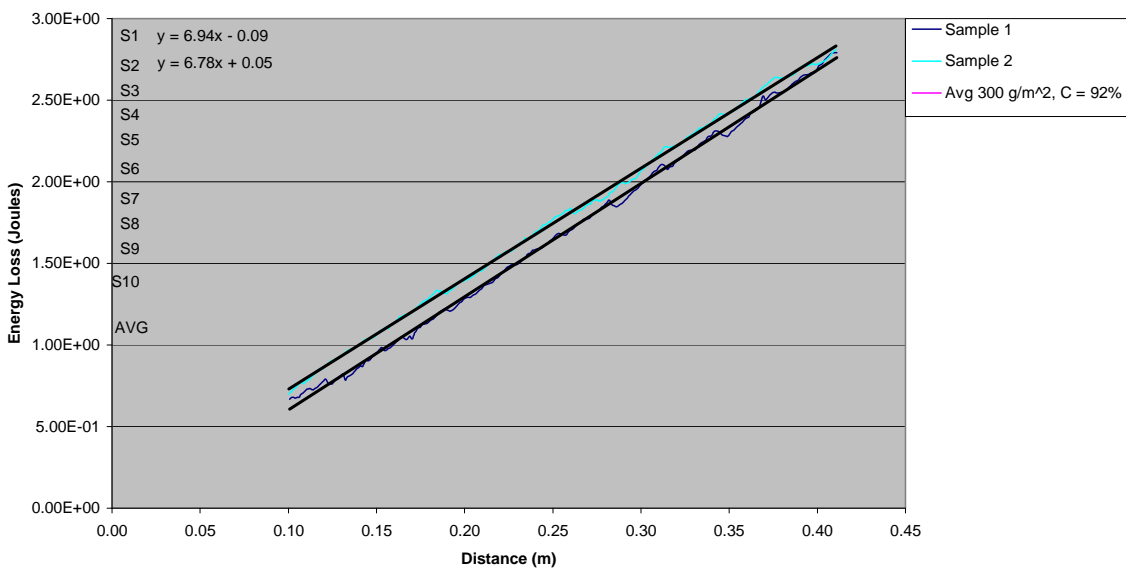
REFINED 770 csf - 300 g/m²
 CONSISTENCY = 67 %
 SPLITTING WEIGHT 1100 gr



REFINED 770 csf - 300 g/m²
 CONSISTENCY = 86 %
 SPLITTING WEIGHT 1100 gr

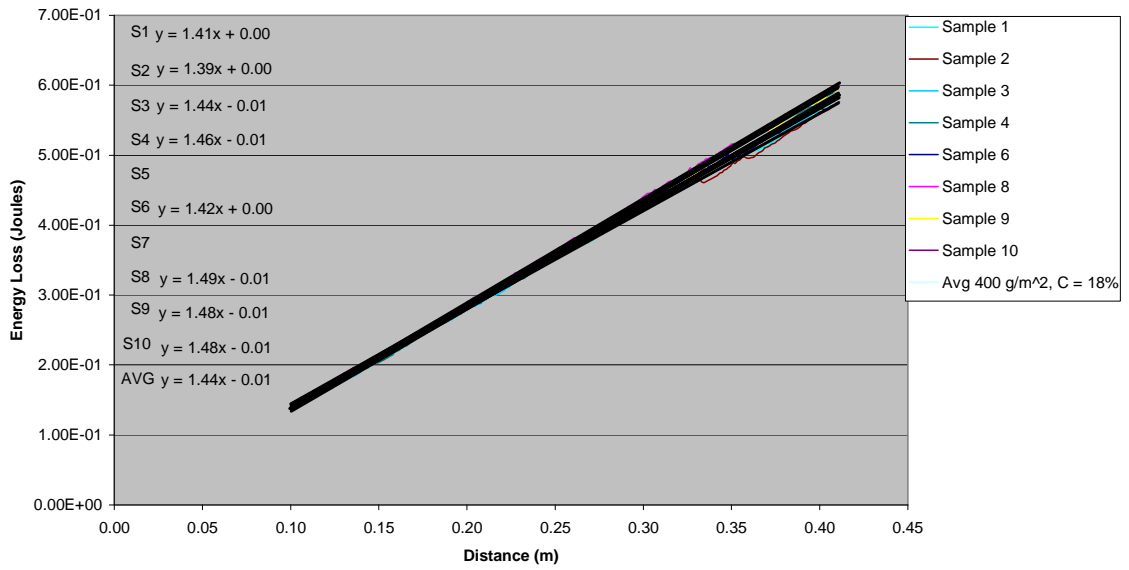


REFINED 770 csf - 300 g/m²
 CONSISTENCY = 92 %
 SPLITTING WEIGHT 1100 gr

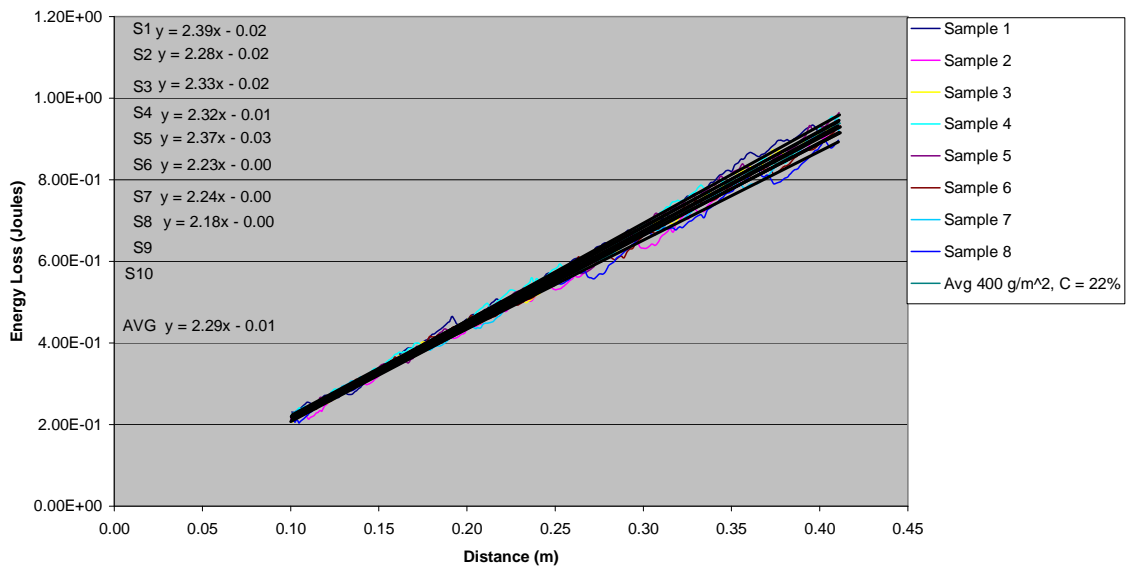


Case 2: Refining 740 C.S.F.; No Chemicals; Basis Weight 396 g/m²

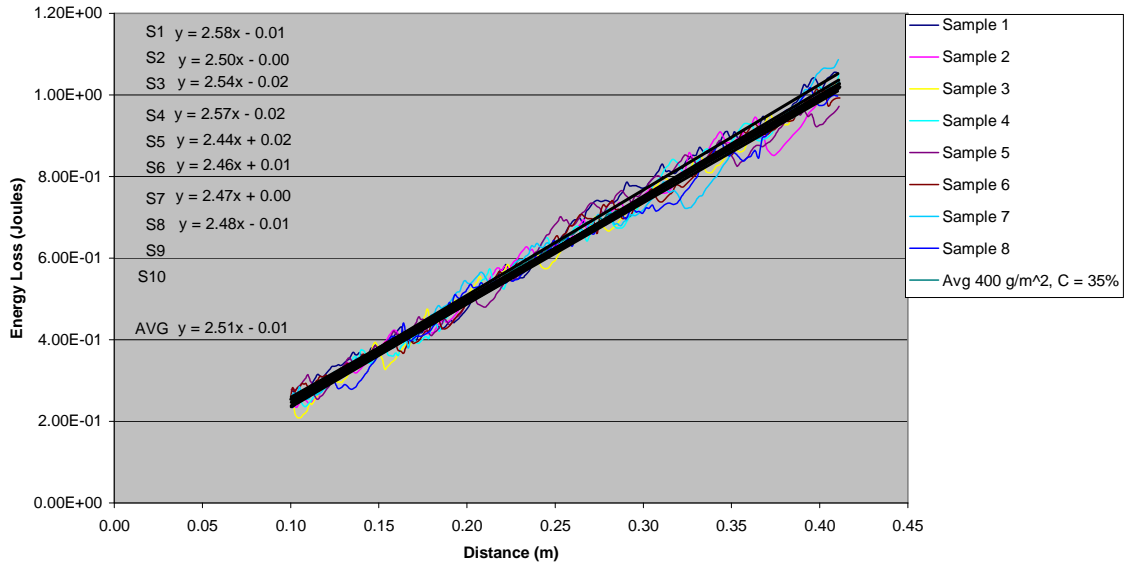
REFINED 770 csf - 400 g/m²
 CONSISTENCY = 18 %
 SPLITTING WEIGHT 250 gr



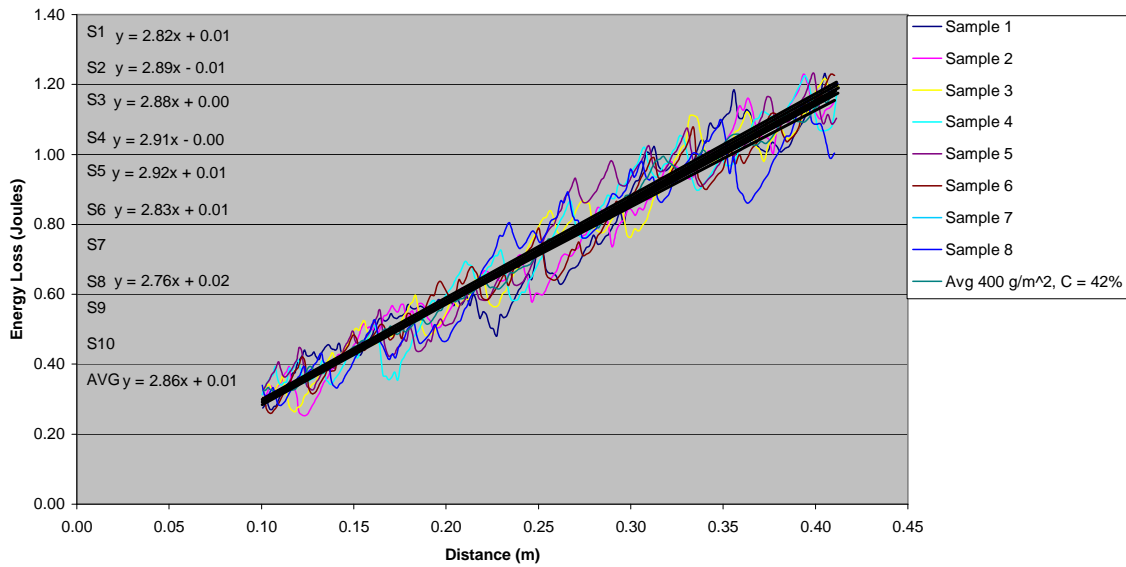
REFINED 770 csf - 400 g/m²
 CONSISTENCY = 22 %
 SPLITTING WEIGHT 466 gr



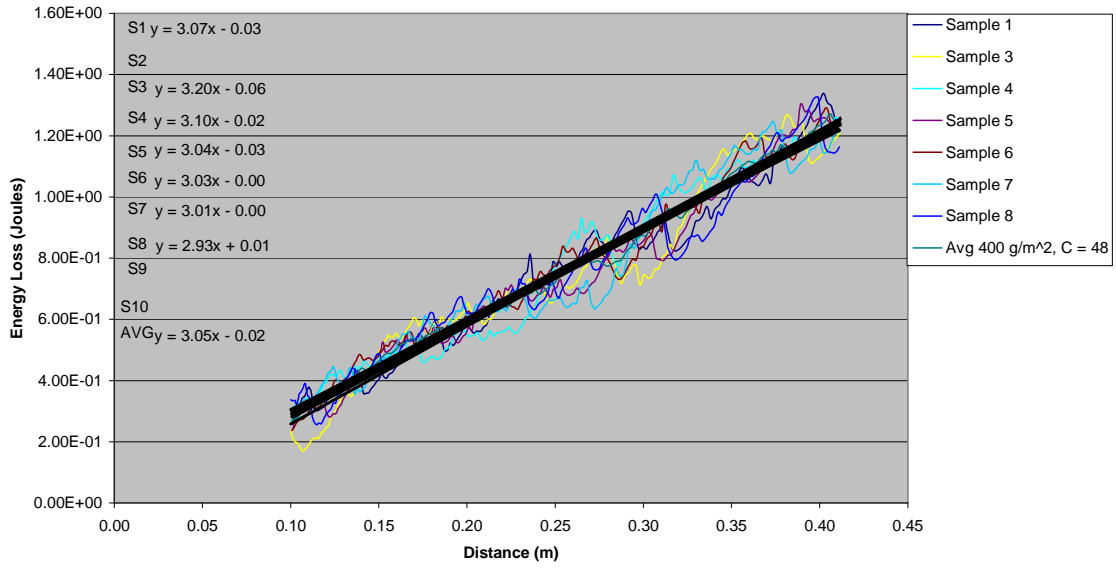
REFINED 770 csf - 400 g/m²
 CONSISTENCY = 35 %
 SPLITTING WEIGHT 660 gr



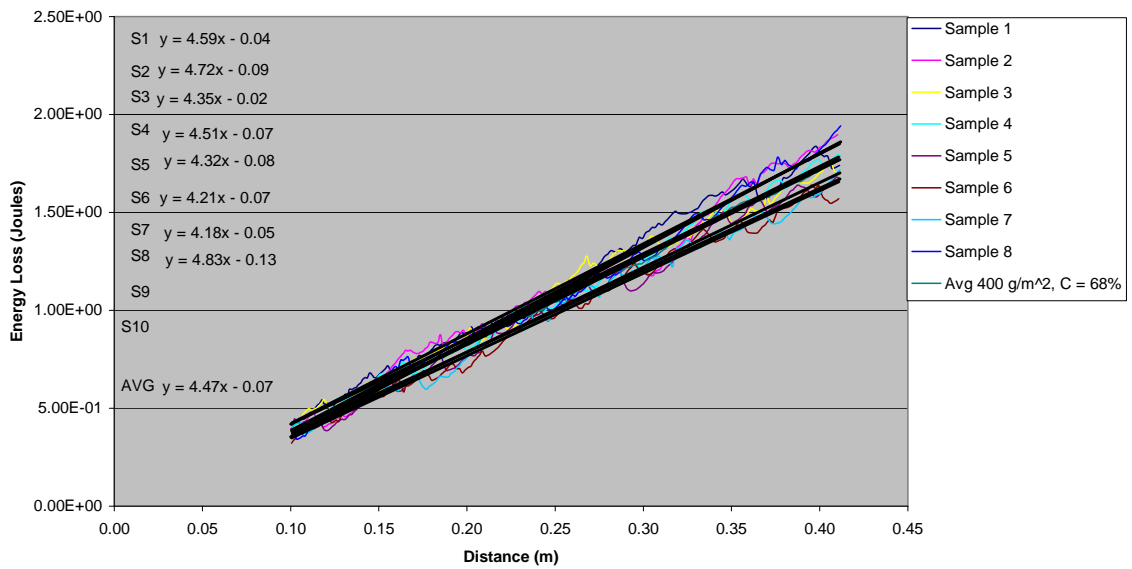
REFINED 770 csf - 400 g/m²
 CONSISTENCY = 42 %
 SPLITTING WEIGHT 1100 gr



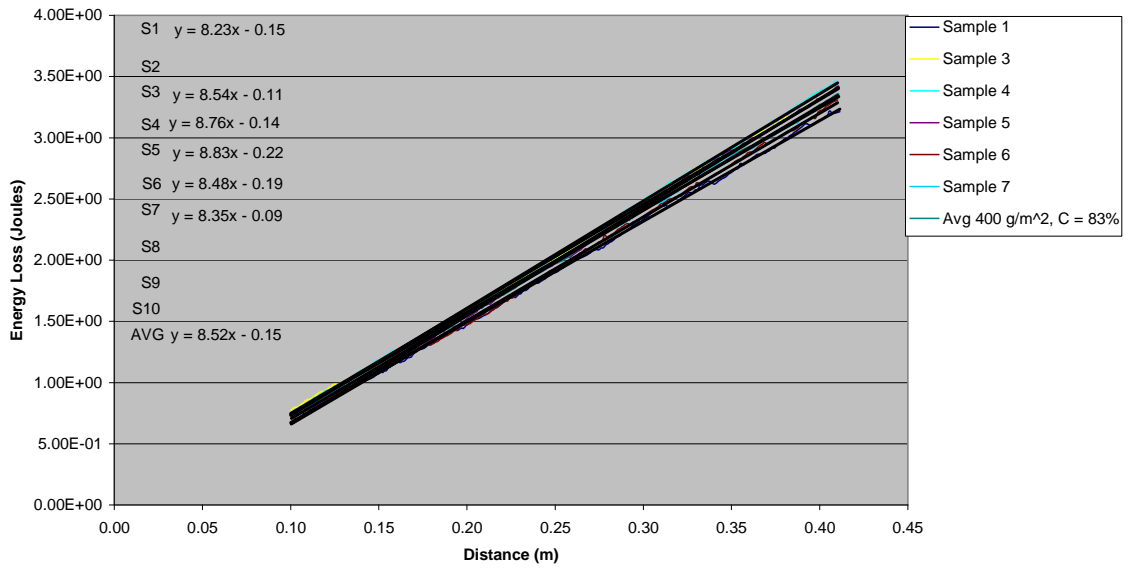
REFINED 770 csf - 400 g/m²
 CONSISTENCY = 48 %
 SPLITTING WEIGHT 1100 gr



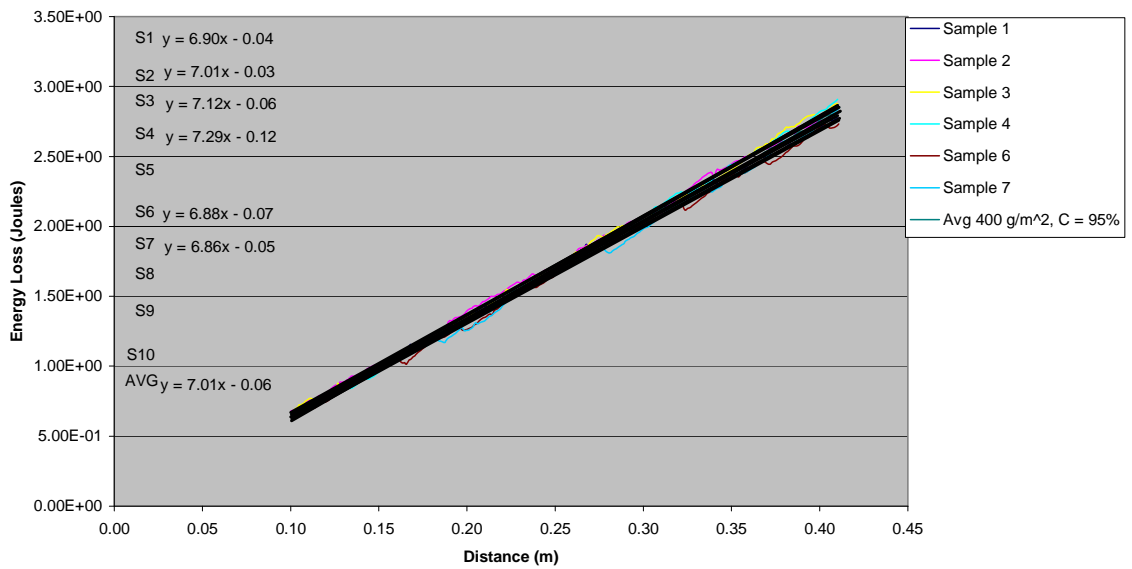
REFINED 770 csf - 400 g/m²
 CONSISTENCY = 68 %
 SPLITTING WEIGHT 1100 gr



REFINED 770 csf - 400 g/m²
 CONSISTENCY = 83 %
 SPLITTING WEIGHT 1100 gr

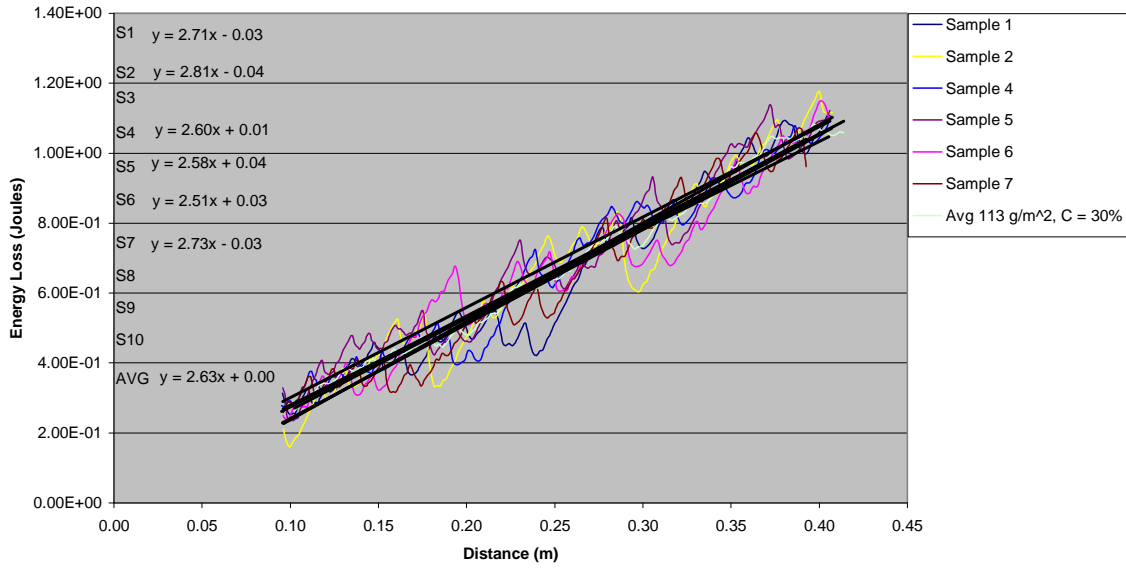


REFINED 770 csf - 400 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

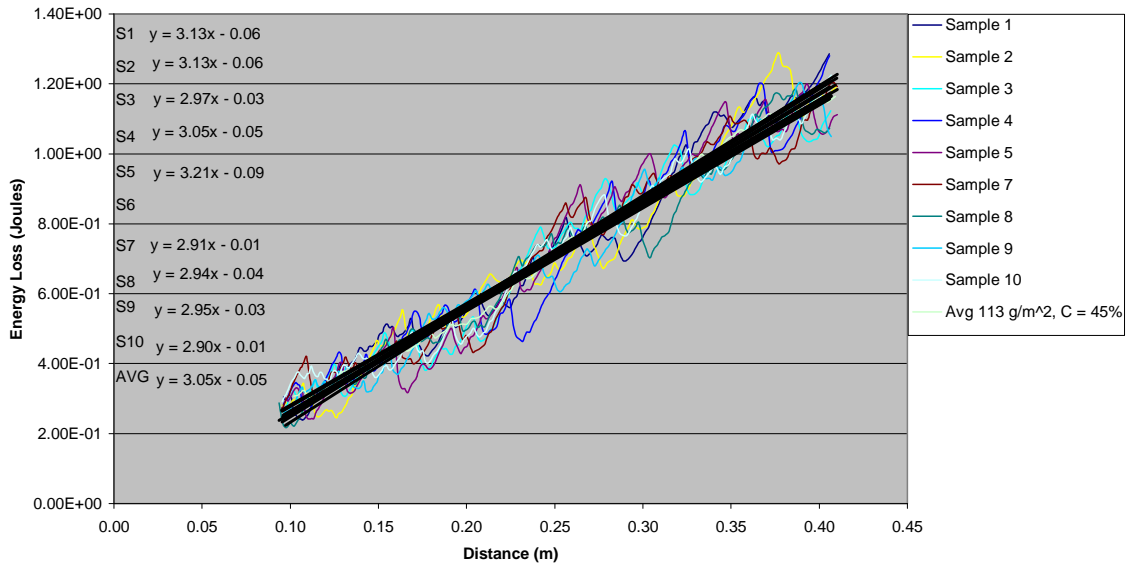


Case 3: Refining 560 C.S.F.; ASH 17% (Normal Clay), No Starch;
Basis Weight 113 g/m²

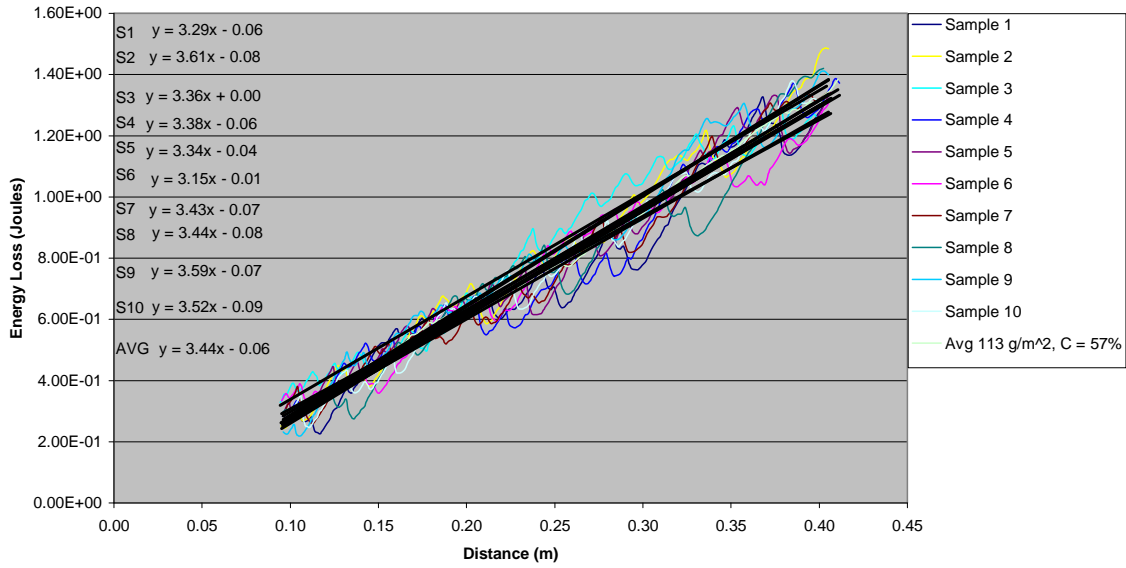
REFINED 560 csf / Ash = 17% - 113 g/m²
 CONSISTENCY = 30 %
 SPLITTING WEIGHT 1100 gr



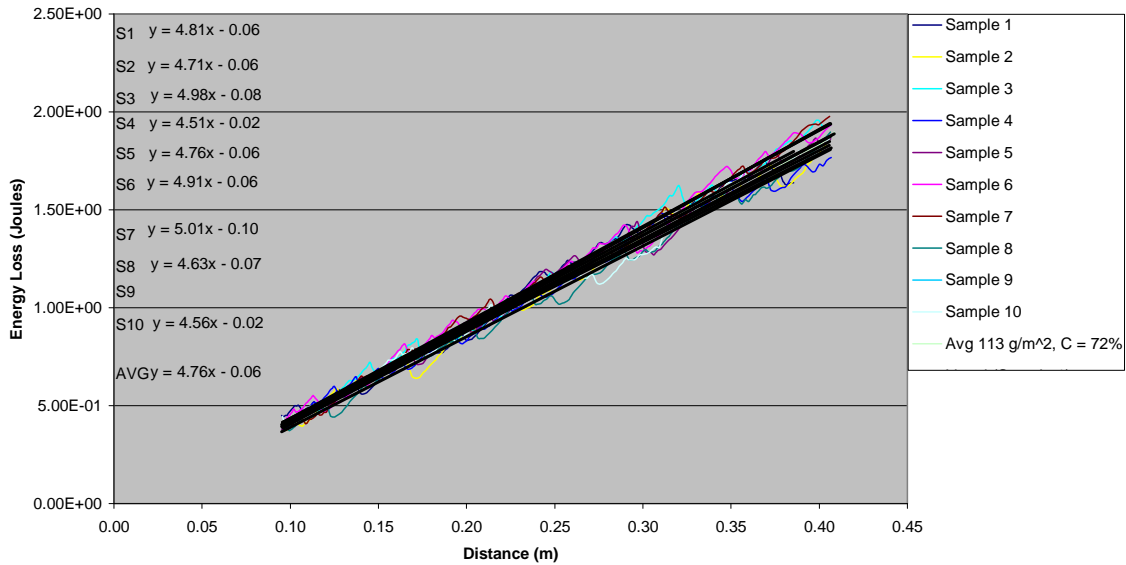
REFINED 560 csf / Ash = 17% - 113 g/m²
 CONSISTENCY = 45 %
 SPLITTING WEIGHT 1100 gr



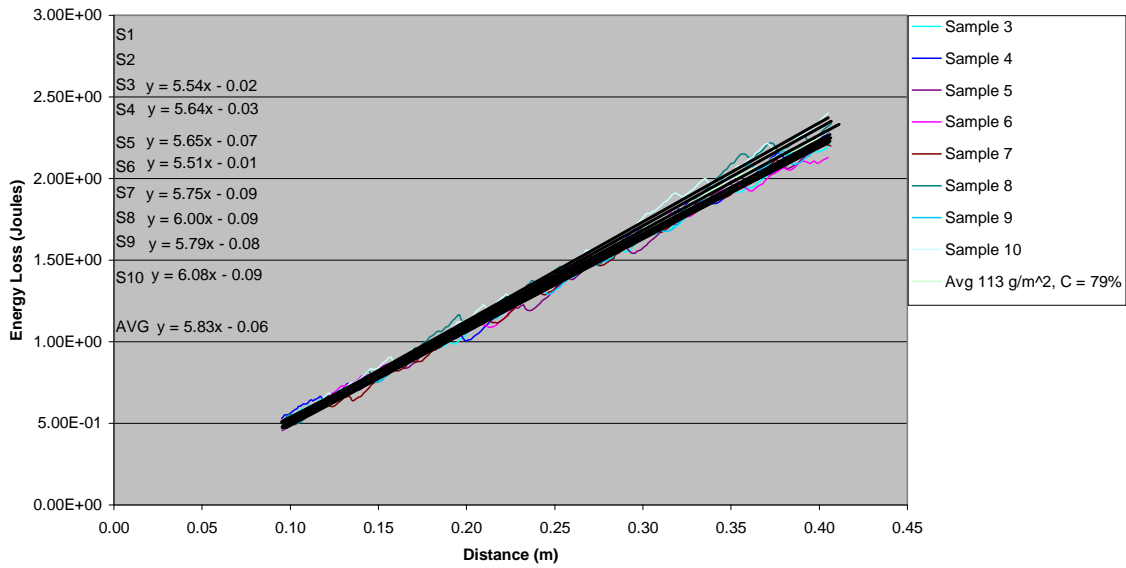
REFINED 560 csf / Ash = 17% - 113 g/m²
 CONSISTENCY = 57 %
 SPLITTING WEIGHT 1100 gr



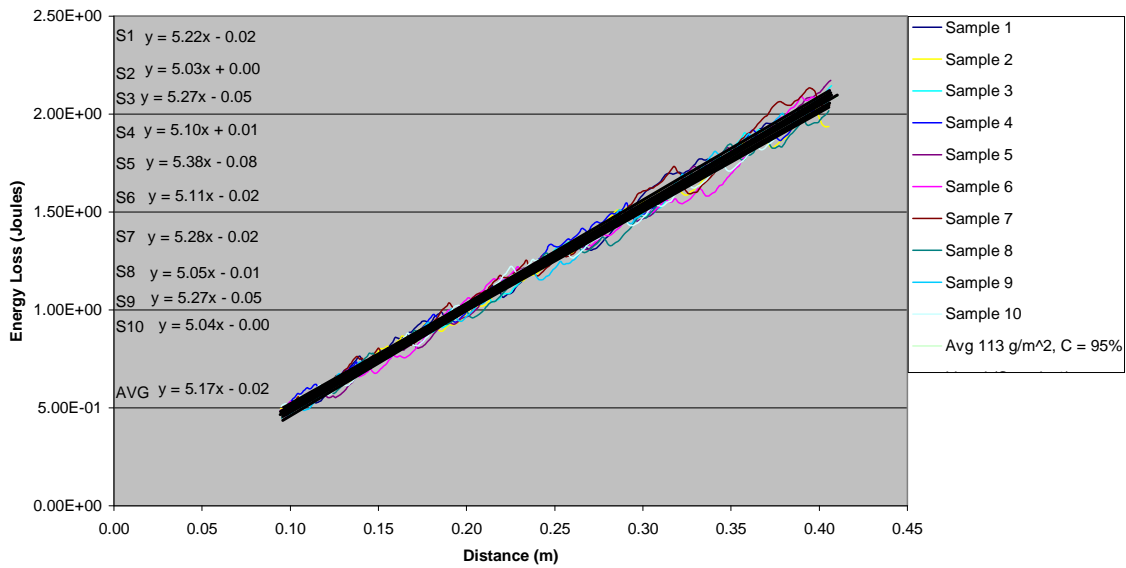
REFINED 560 csf / Ash = 17% - 113 g/m²
 CONSISTENCY = 72 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 17% - 113 g/m²
 CONSISTENCY = 79 %
 SPLITTING WEIGHT 1100 gr

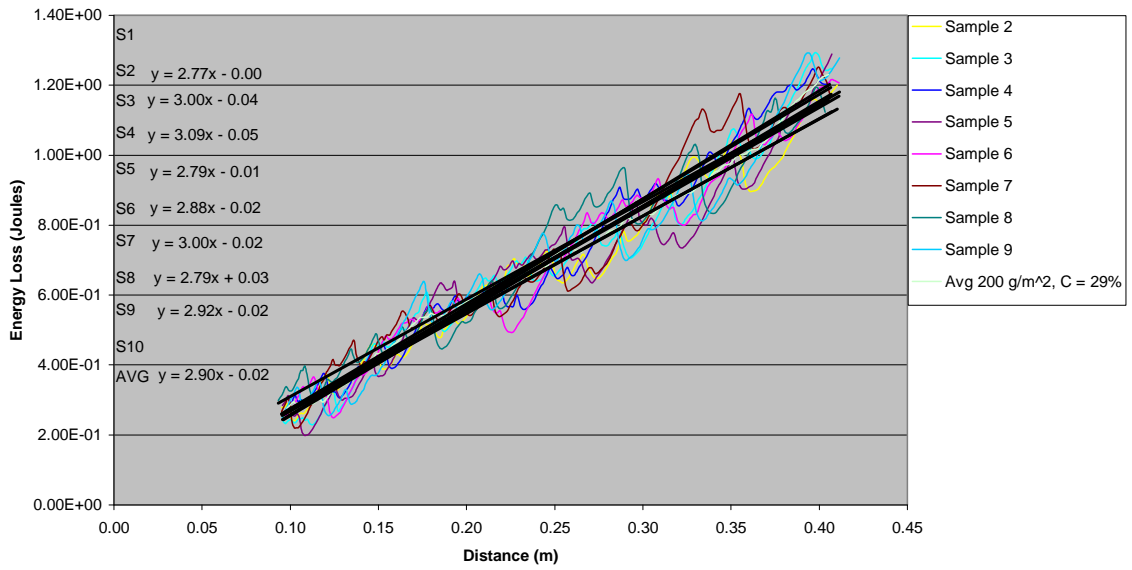


REFINED 560 csf / Ash = 17% - 113 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

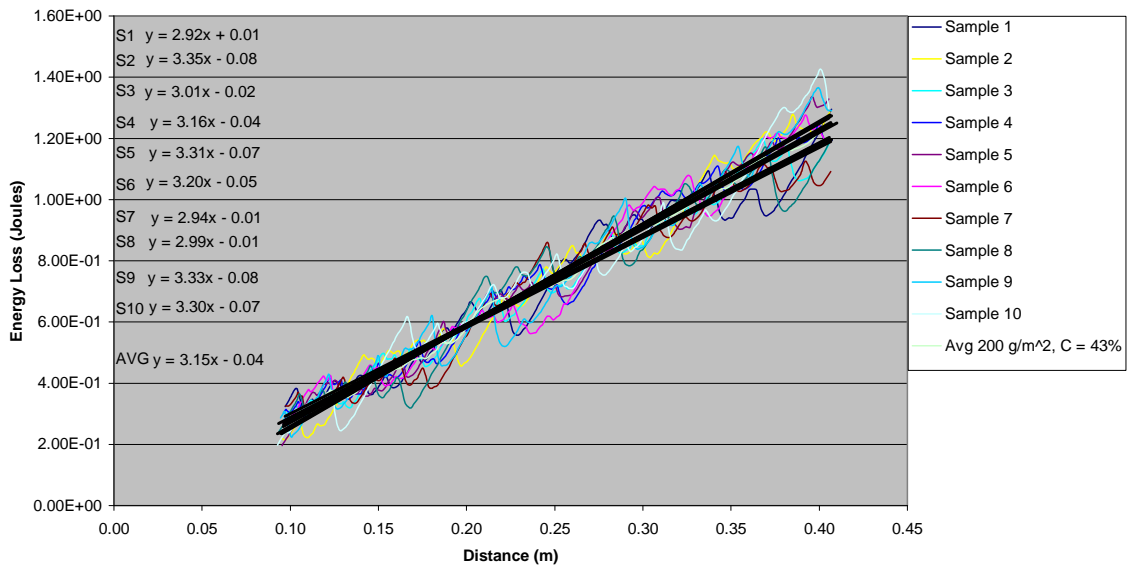


Case 3: Refining 560 C.S.F.; ASH 17% (Normal Clay), No Starch;
Basis Weight 202 g/m²

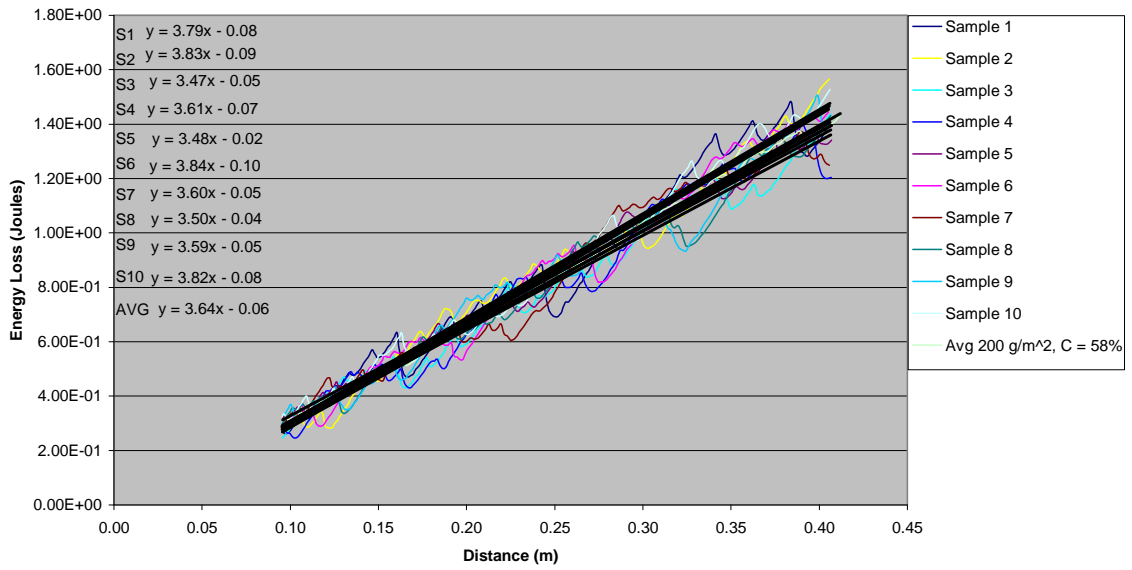
REFINED 560 csf / Ash = 17% - 200 g/m²
 CONSISTENCY = 29 %
 SPLITTING WEIGHT 1100 gr



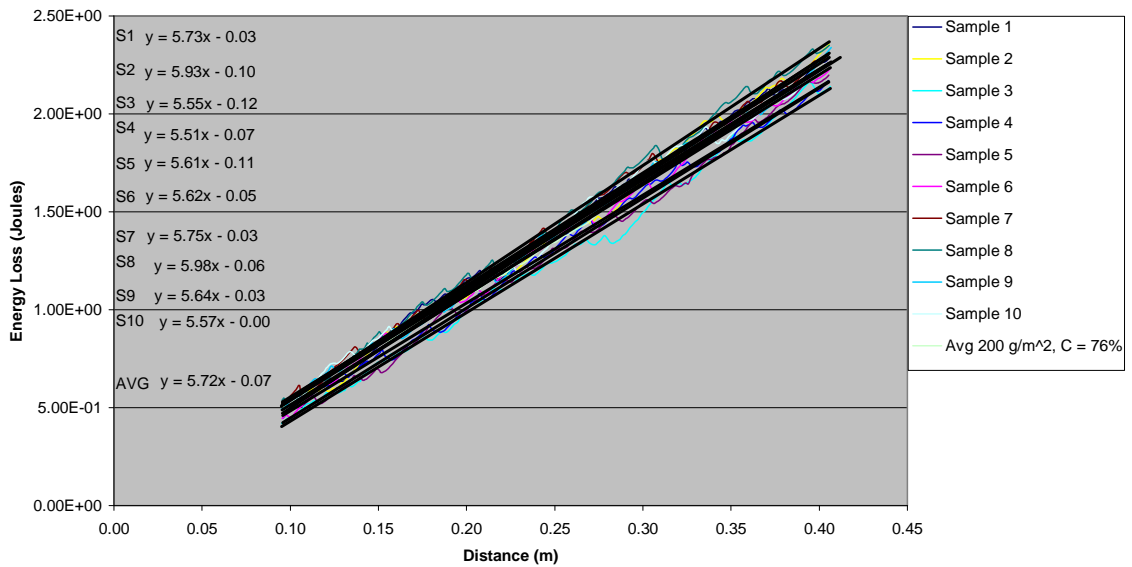
REFINED 560 csf / Ash = 17% - 200 g/m²
 CONSISTENCY = 43 %
 SPLITTING WEIGHT 1100 gr



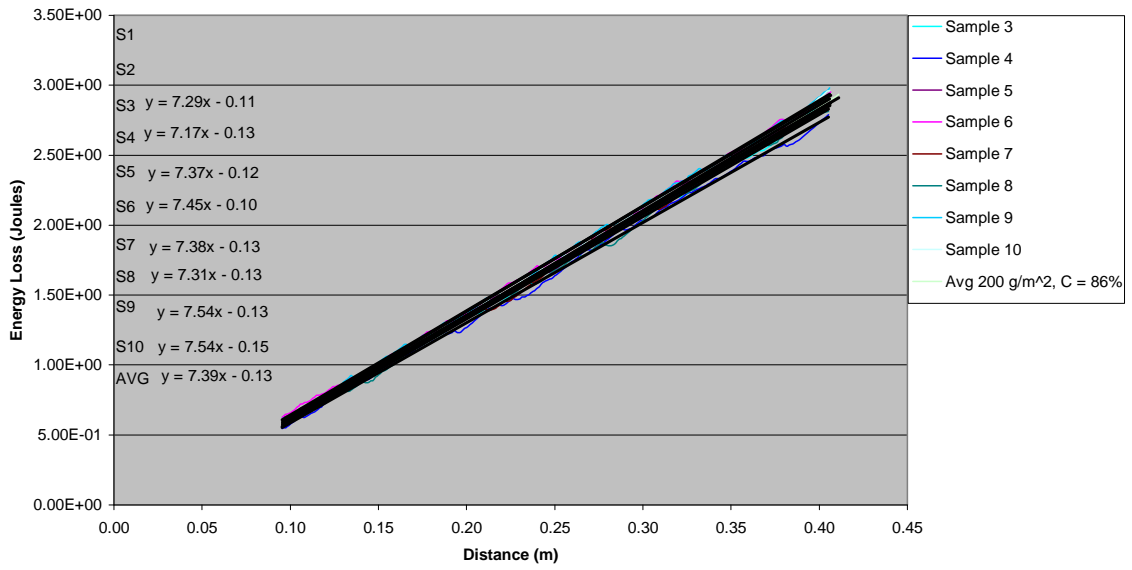
REFINED 560 csf / Ash = 17% - 200 g/m²
 CONSISTENCY = 58 %
 SPLITTING WEIGHT 1100 gr



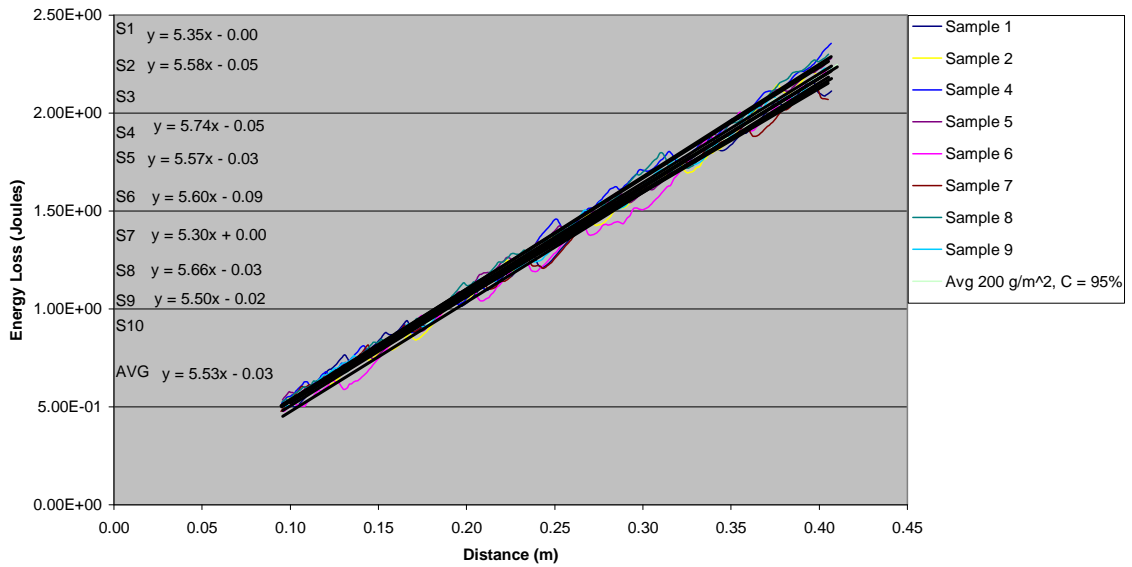
REFINED 560 csf / Ash = 17% - 200 g/m²
 CONSISTENCY = 76 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 17% - 200 g/m²
 CONSISTENCY = 86 %
 SPLITTING WEIGHT 1100 gr

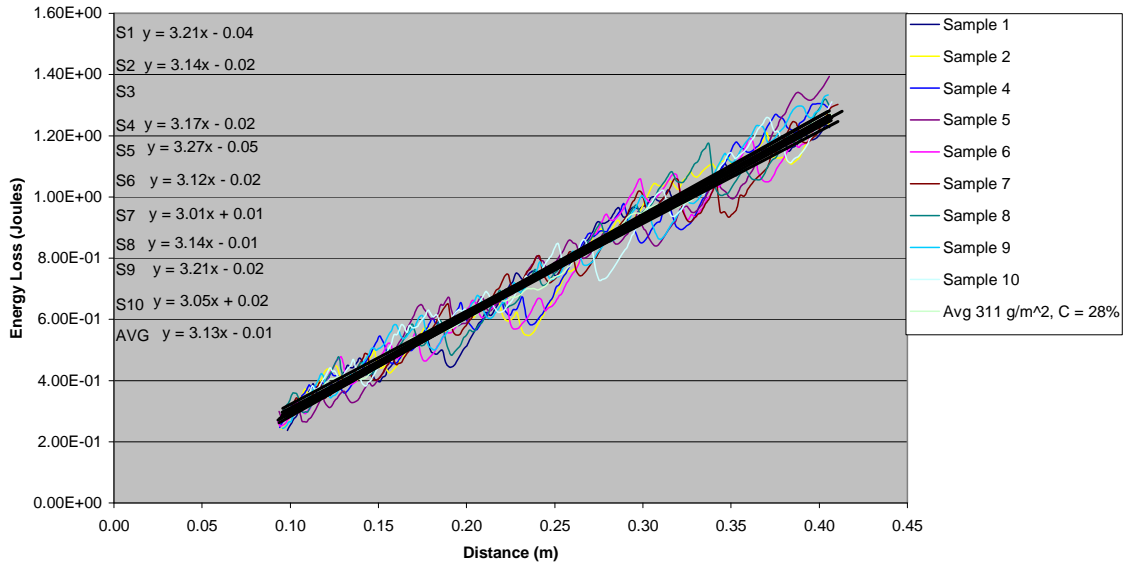


REFINED 560 csf / Ash = 17% - 200 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

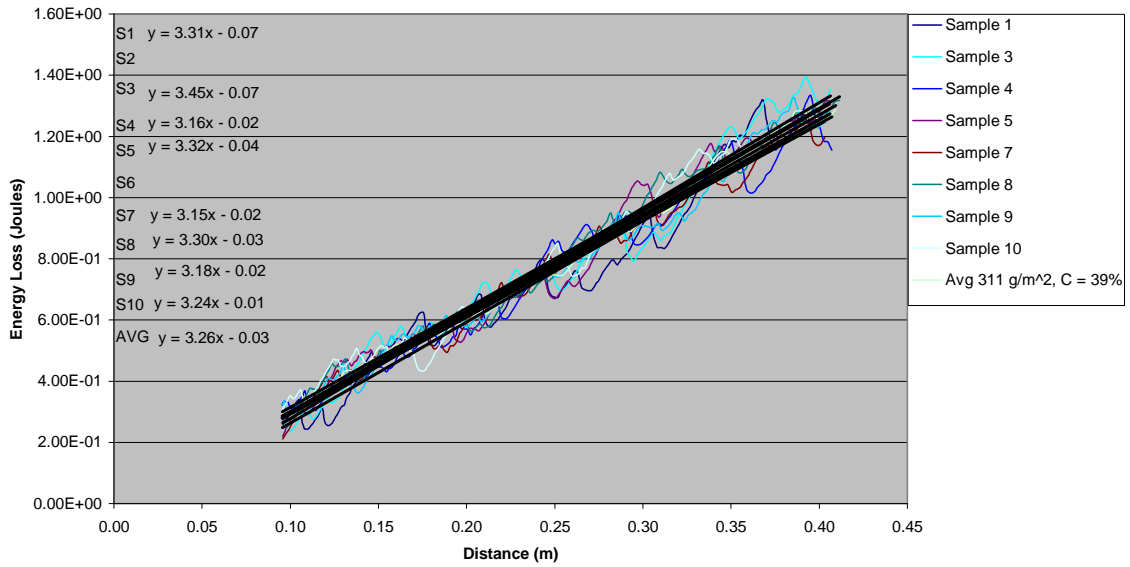


Case 3: Refining 560 C.S.F.; ASH 17% (Normal Clay), No Starch;
Basis Weight 311 g/m²

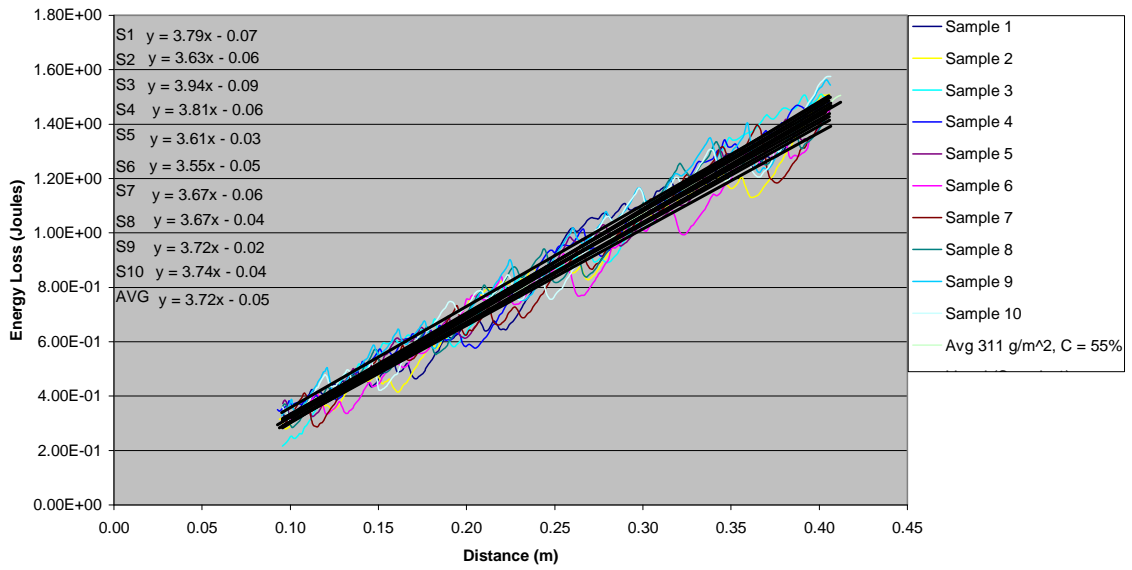
REFINED 560 csf / Ash = 17% - 311 g/m²
 CONSISTENCY = 28 %
 SPLITTING WEIGHT 1100 gr



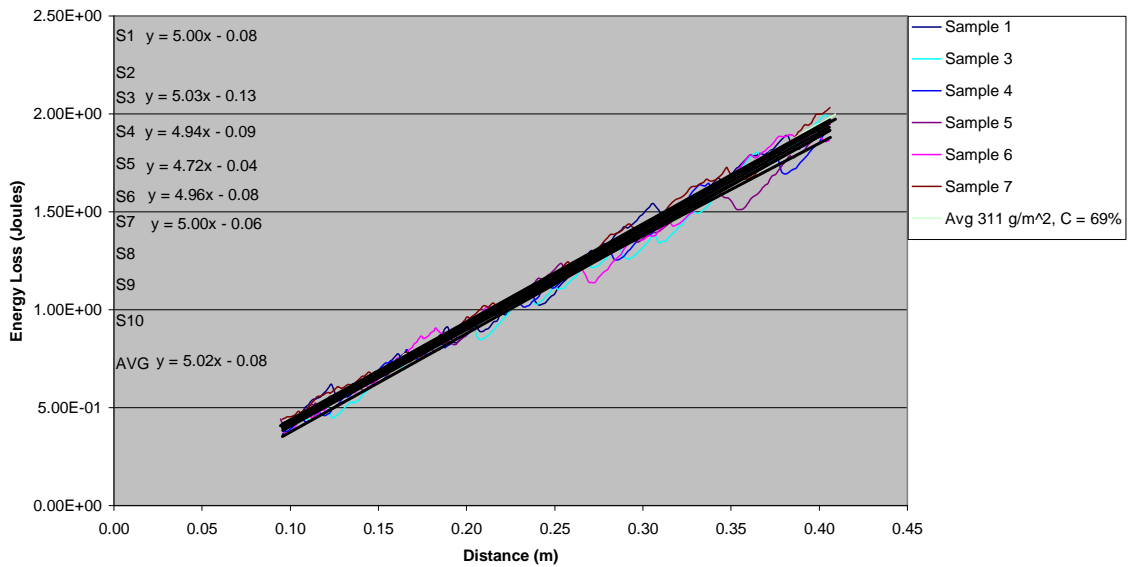
REFINED 560 csf / Ash = 17% - 311 g/m²
 CONSISTENCY = 39 %
 SPLITTING WEIGHT 1100 gr



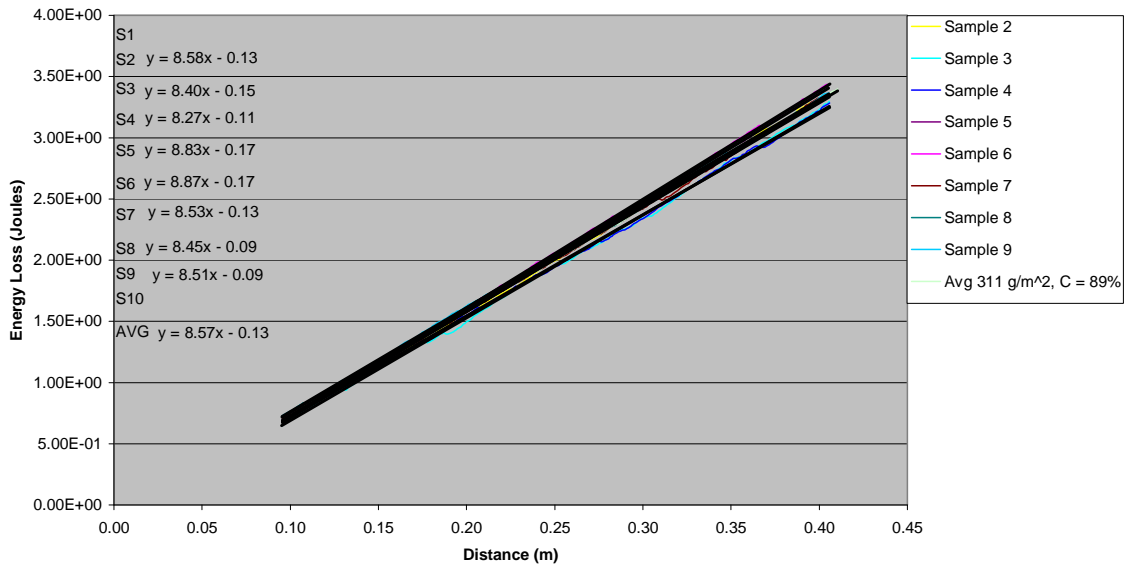
REFINED 560 csf / Ash = 17% - 311 g/m²
 CONSISTENCY = 55 %
 SPLITTING WEIGHT 1100 gr



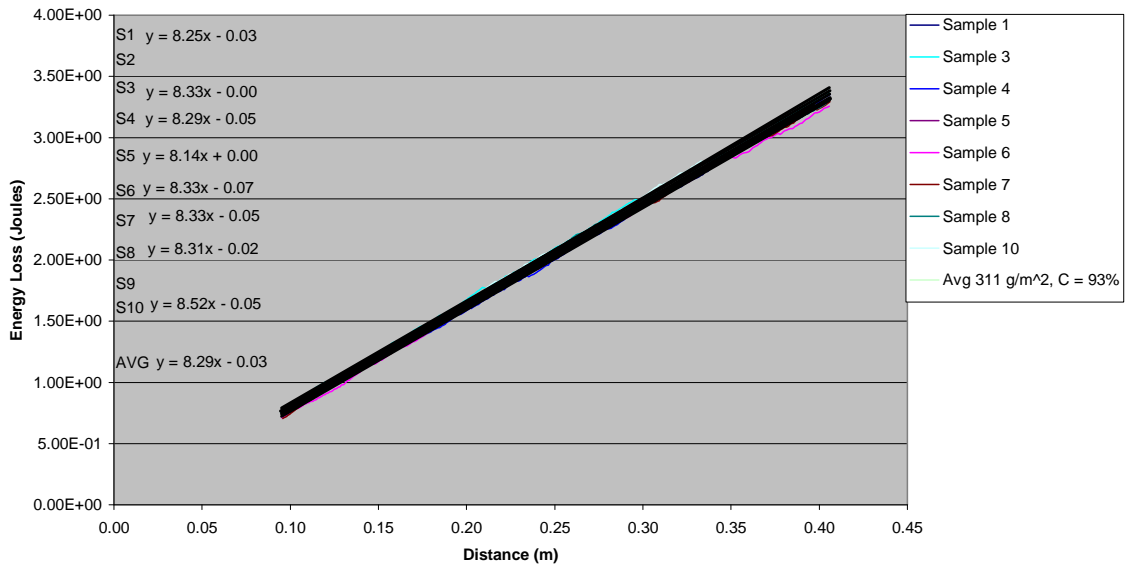
REFINED 560 csf / Ash = 17% - 311 g/m²
 CONSISTENCY = 69 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 17% - 311 g/m²
 CONSISTENCY = 89 %
 SPLITTING WEIGHT 1100 gr

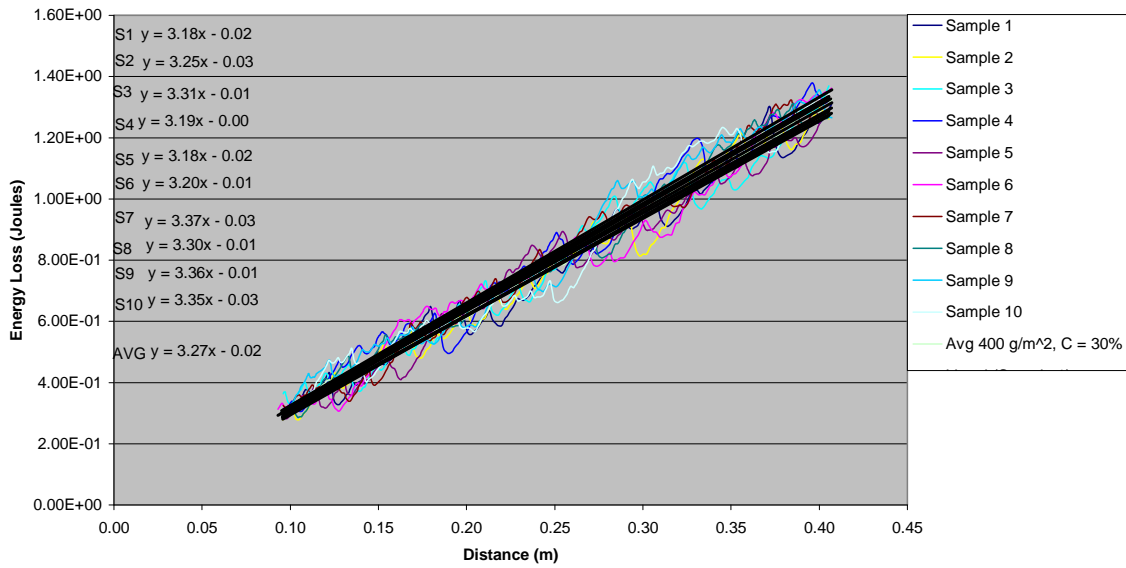


REFINED 560 csf / Ash = 17% - 311 g/m²
 CONSISTENCY = 93 %
 SPLITTING WEIGHT 1100 gr

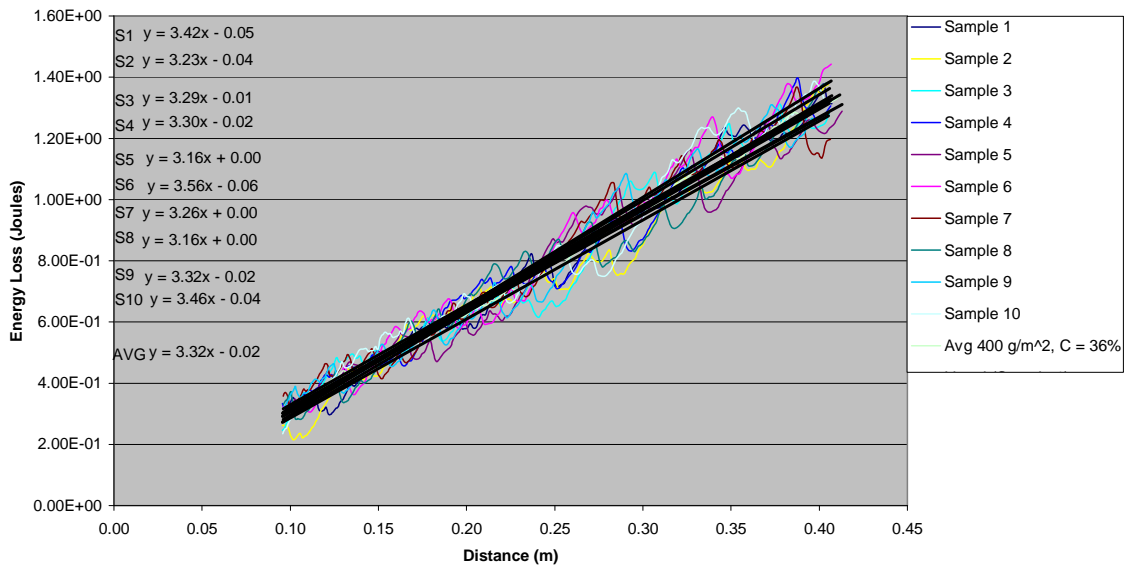


Case 3: Refining 560 C.S.F.; ASH 17% (Normal Clay), No Starch;
Basis Weight 400 g/m²

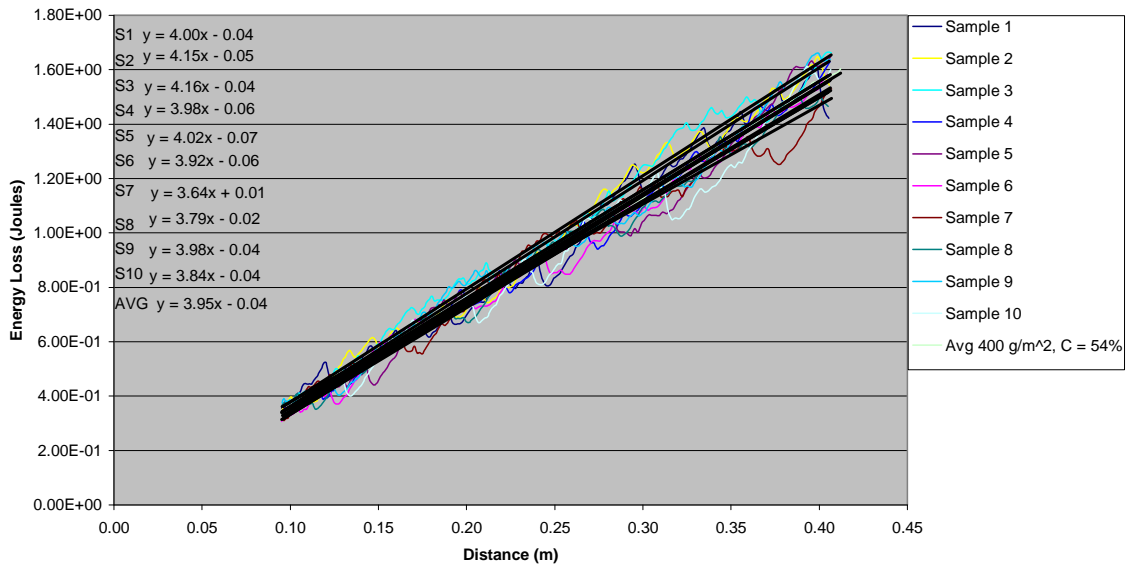
REFINED 560 csf / Ash = 17% - 400 g/m²
 CONSISTENCY = 30 %
 SPLITTING WEIGHT 1100 gr



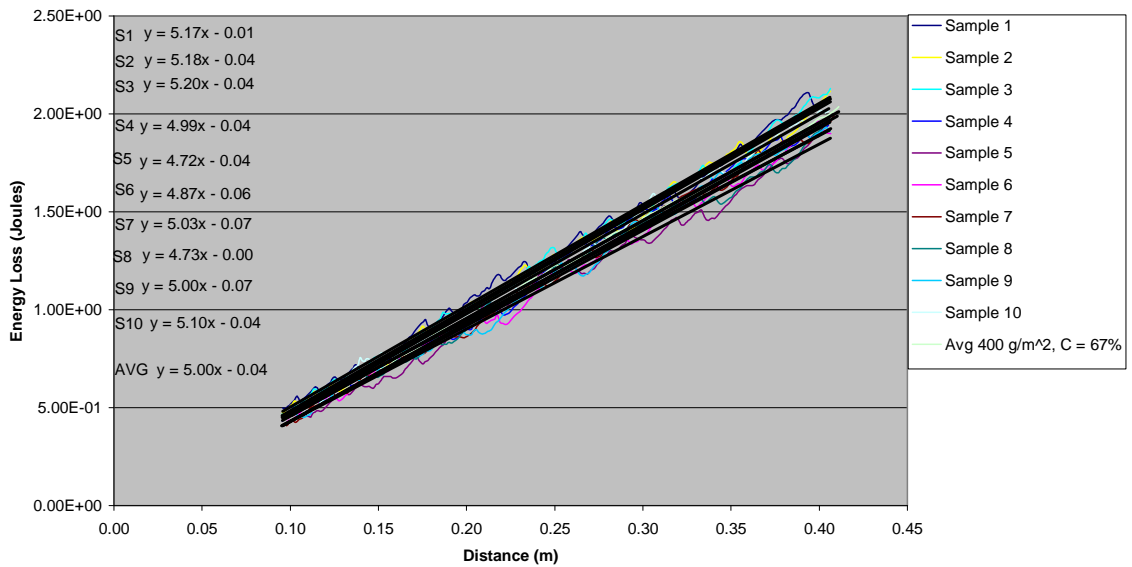
REFINED 560 csf / Ash = 17% - 400 g/m²
 CONSISTENCY = 36 %
 SPLITTING WEIGHT 1100 gr



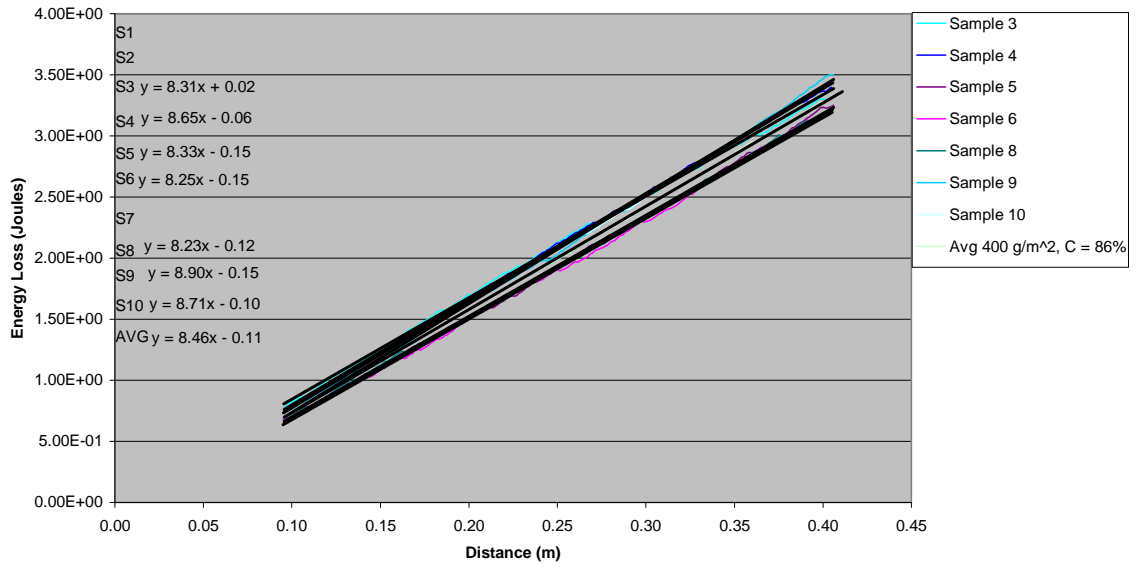
REFINED 560 csf / Ash = 17% - 400 g/m²
 CONSISTENCY = 54 %
 SPLITTING WEIGHT 1100 gr



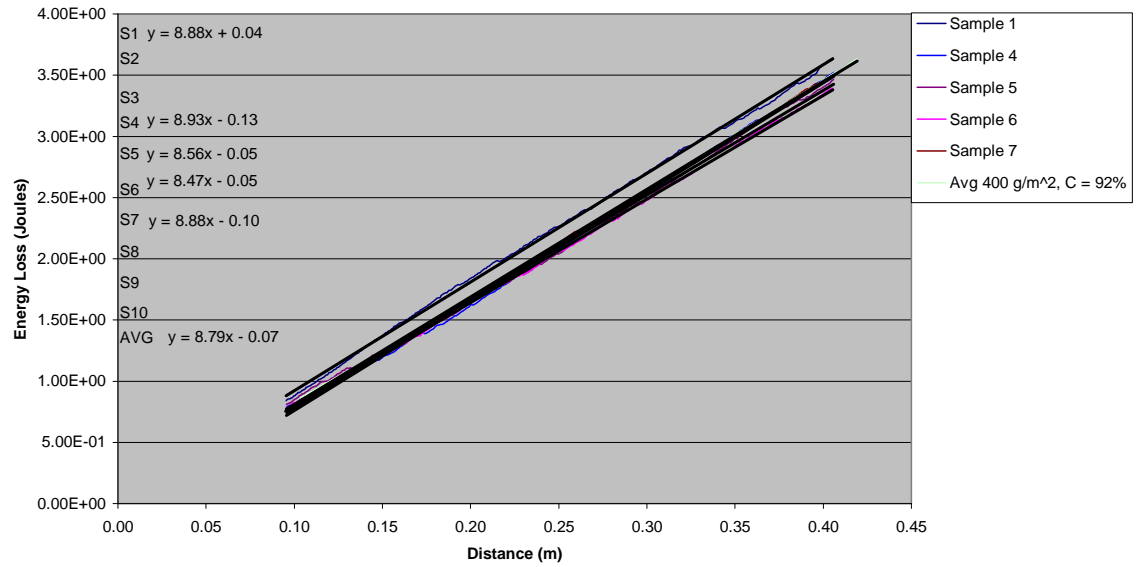
REFINED 560 csf / Ash = 17% - 400 g/m²
 CONSISTENCY = 67 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 17% - 400 g/m²
 CONSISTENCY = 86 %
 SPLITTING WEIGHT 1100 gr

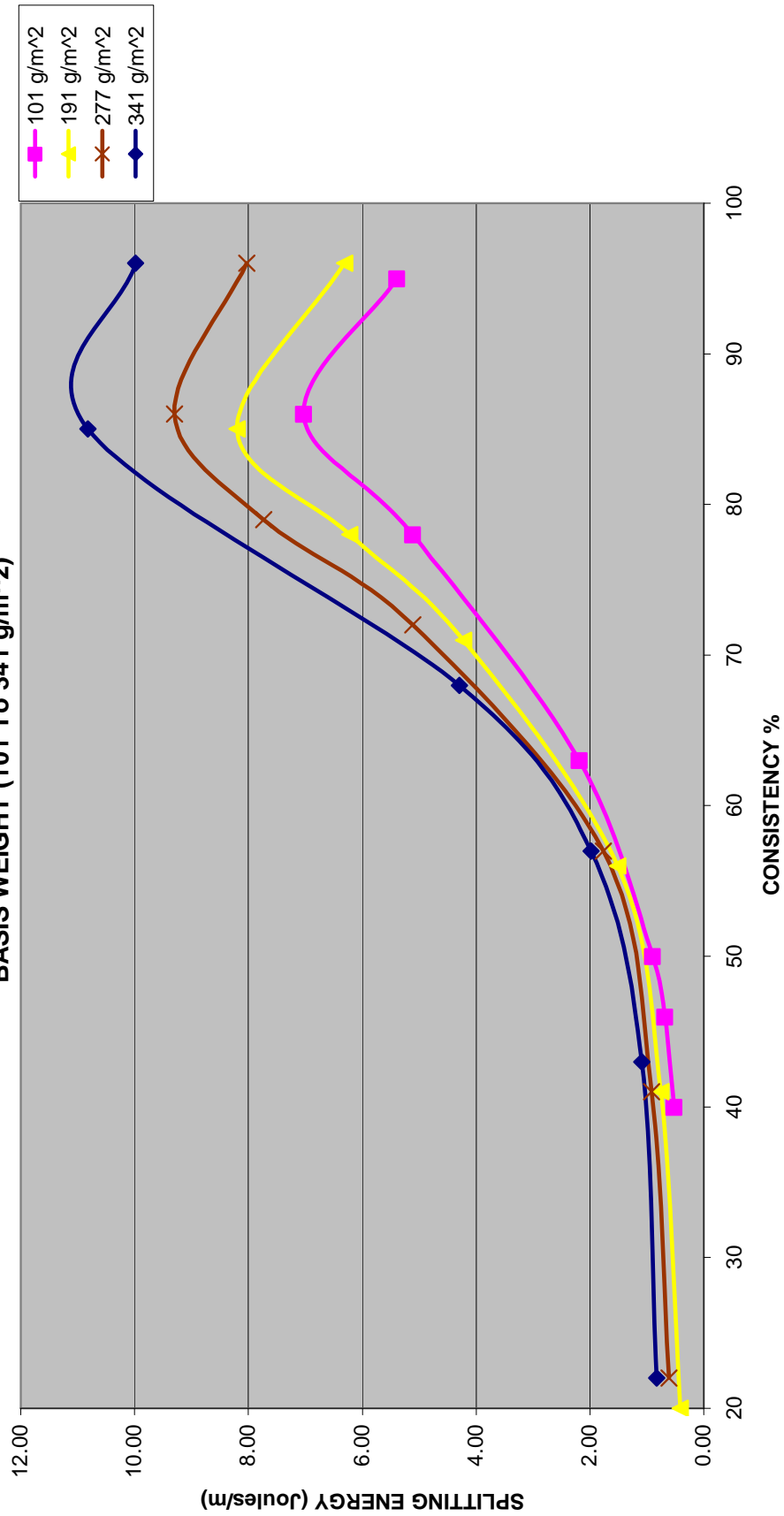


REFINED 560 csf / Ash = 17% - 400 g/m²
 CONSISTENCY = 92 %
 SPLITTING WEIGHT 1100 gr

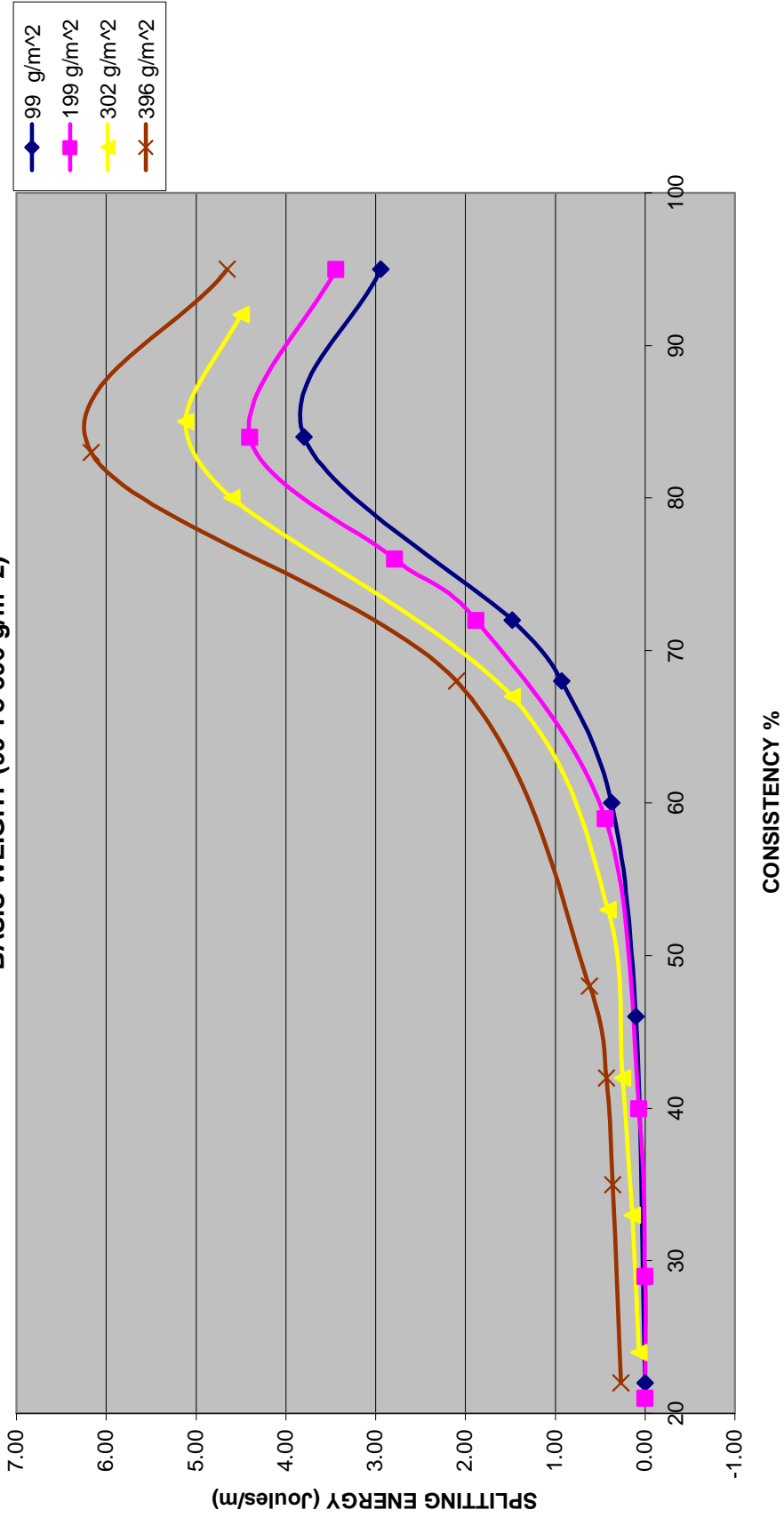


APPENDIX A.2: SPLITTING ENERGY VS PAPER SOLIDS – CASES 1 TO 3

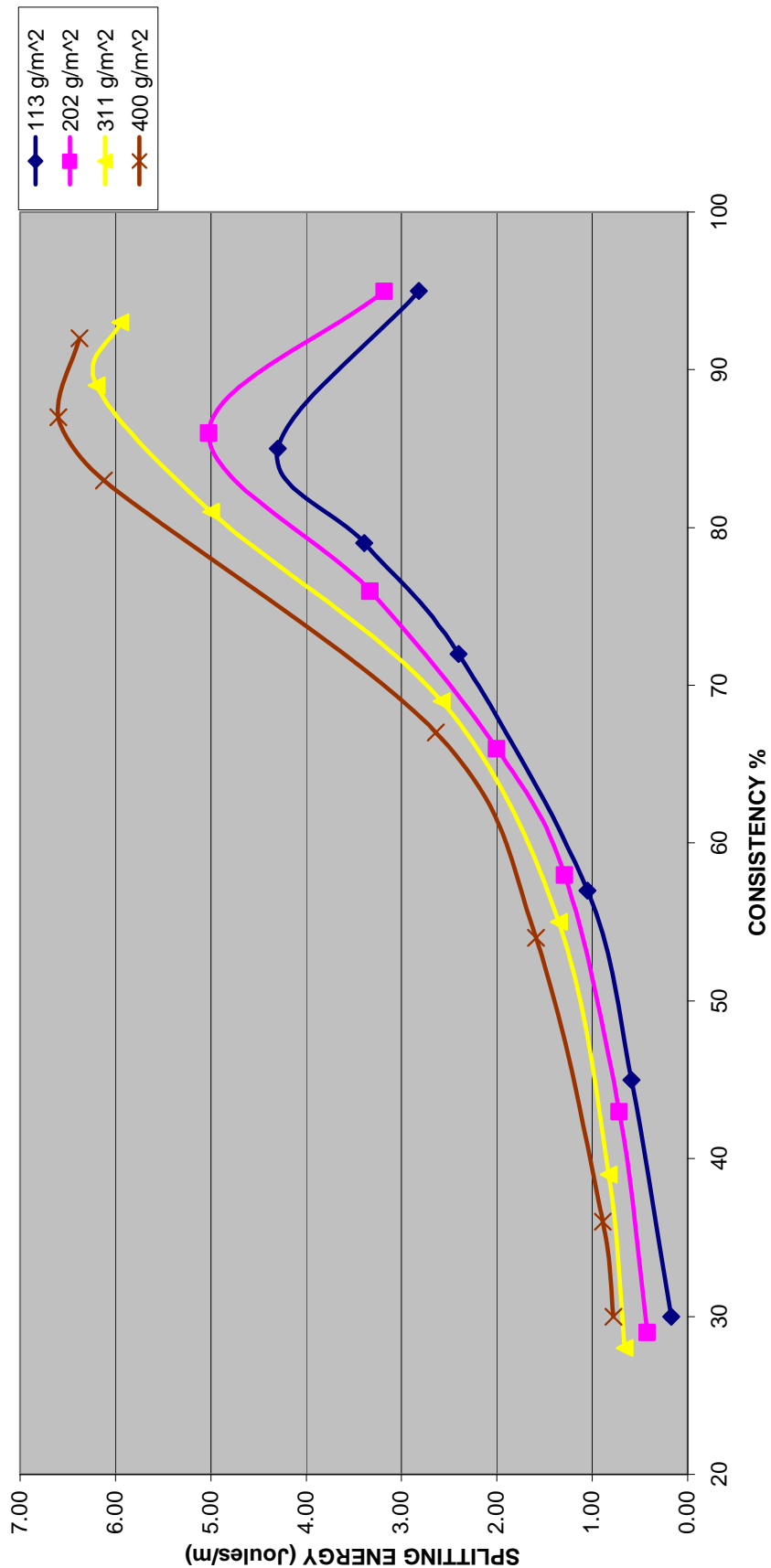
SPLITTING ENERGY Vs PAPER CONSISTENCY
CASE 1
REFINING 560 csf; NO CHEMICALS
BASIS WEIGHT (101 To 341 g/m²)



SPLITTING ENERGY Vs PAPER CONSISTENCY
CASE 2
REFINING 740 csf; NO CHEMICALS
BASIS WEIGHT (99 To 396 g/m²)



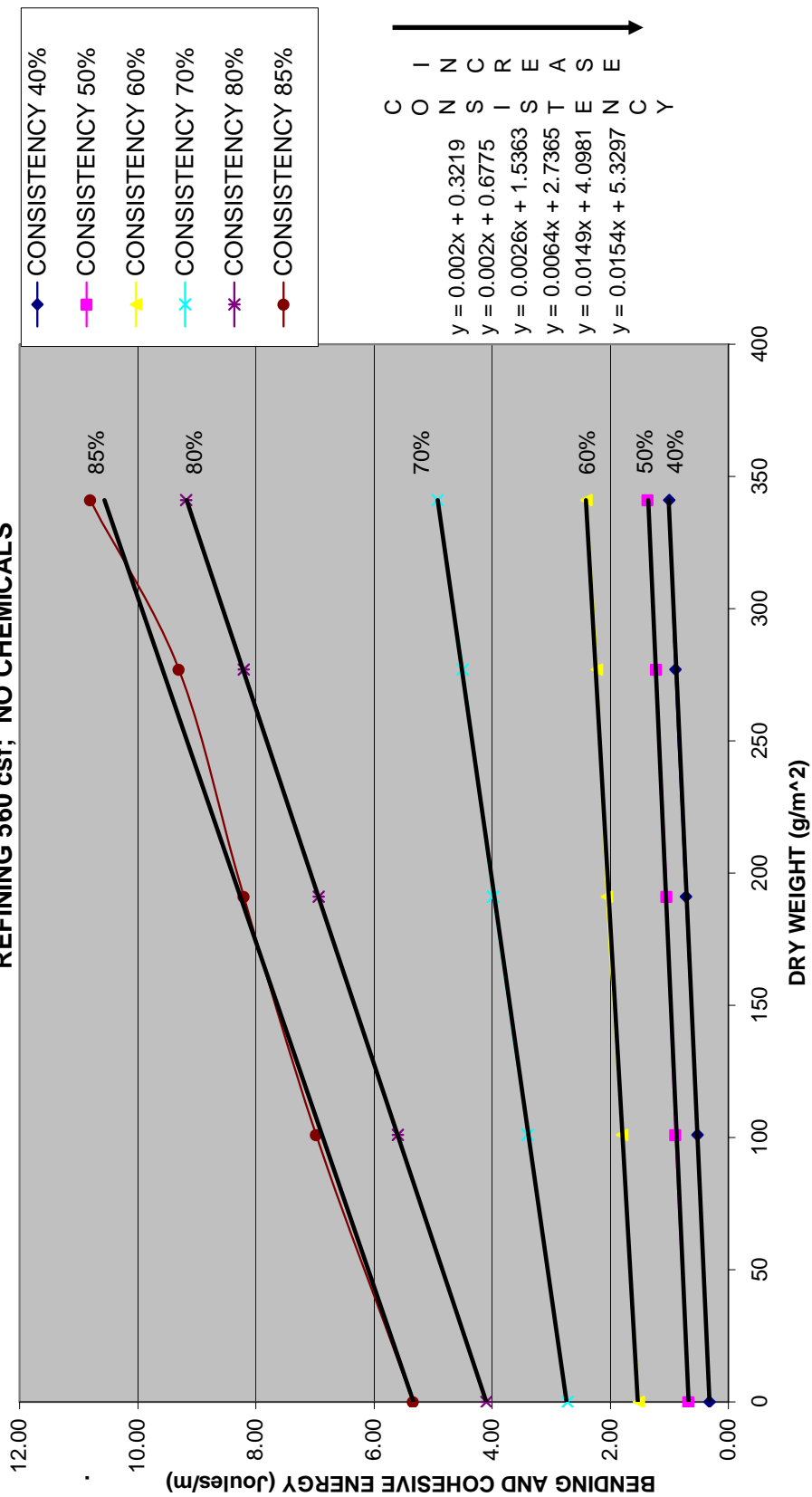
SPLITTING ENERGY Vs PAPER CONSISTENCY
CASE 3
REFINING 560 csf; ASH CONTENT = 17% (Normal Clay), C-PAM 0.1kg/Ton & NO STARCH
BASIS WEIGHT (113 To 400 g/m²)



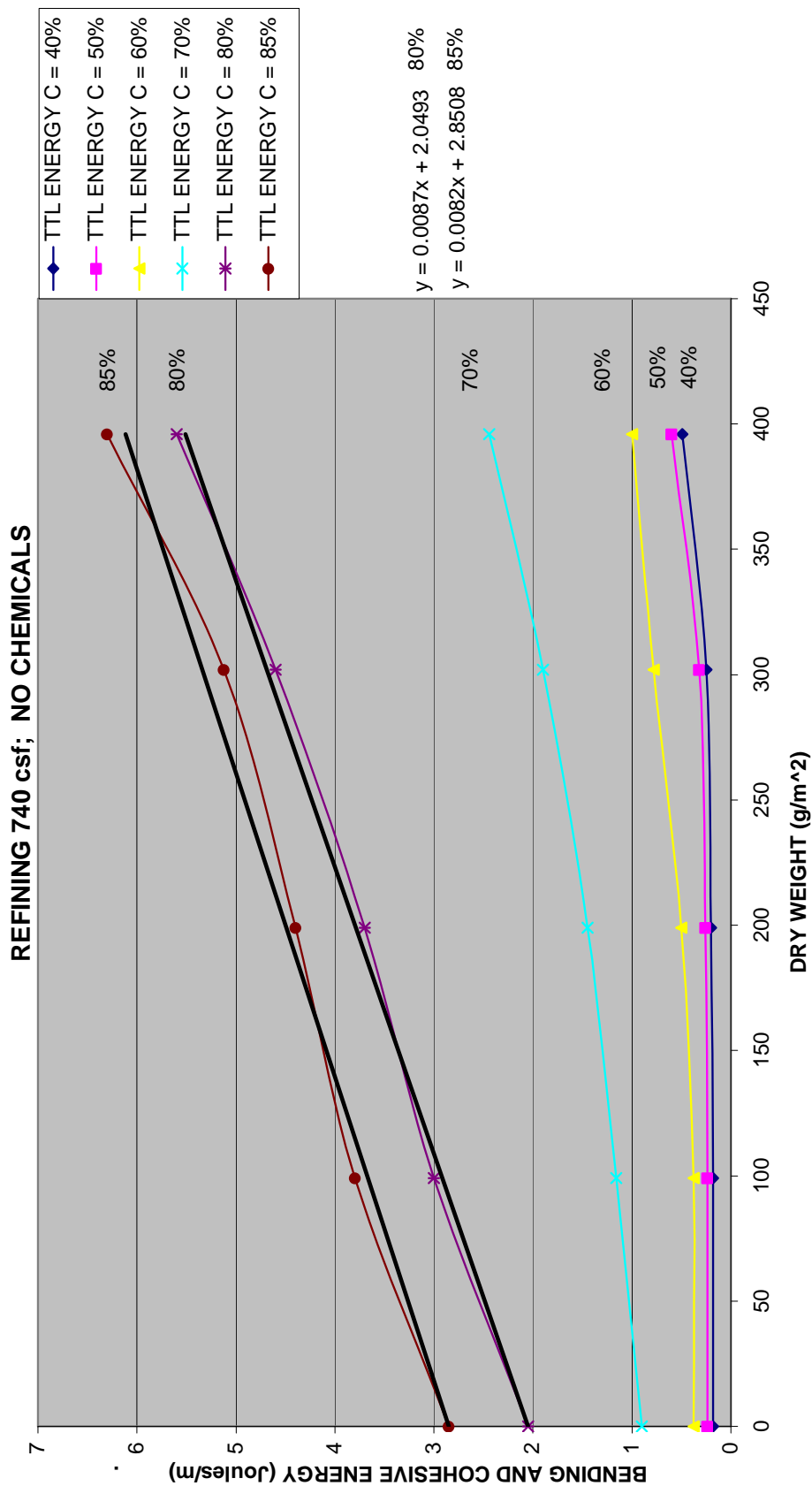
APPENDIX A.3: COHESIVE ENERGY DETERMINATION AT DIFFERENT SOLIDS – CASES 1 TO 3

BENDING AND COHESIVE ENERGY Vs DRY WEIGHT **"Y" INTERSECTION CORRESPONDS TO THE COHESIVE ENERGY** **CASE 1**

REFINING 560 csf; NO CHEMICALS



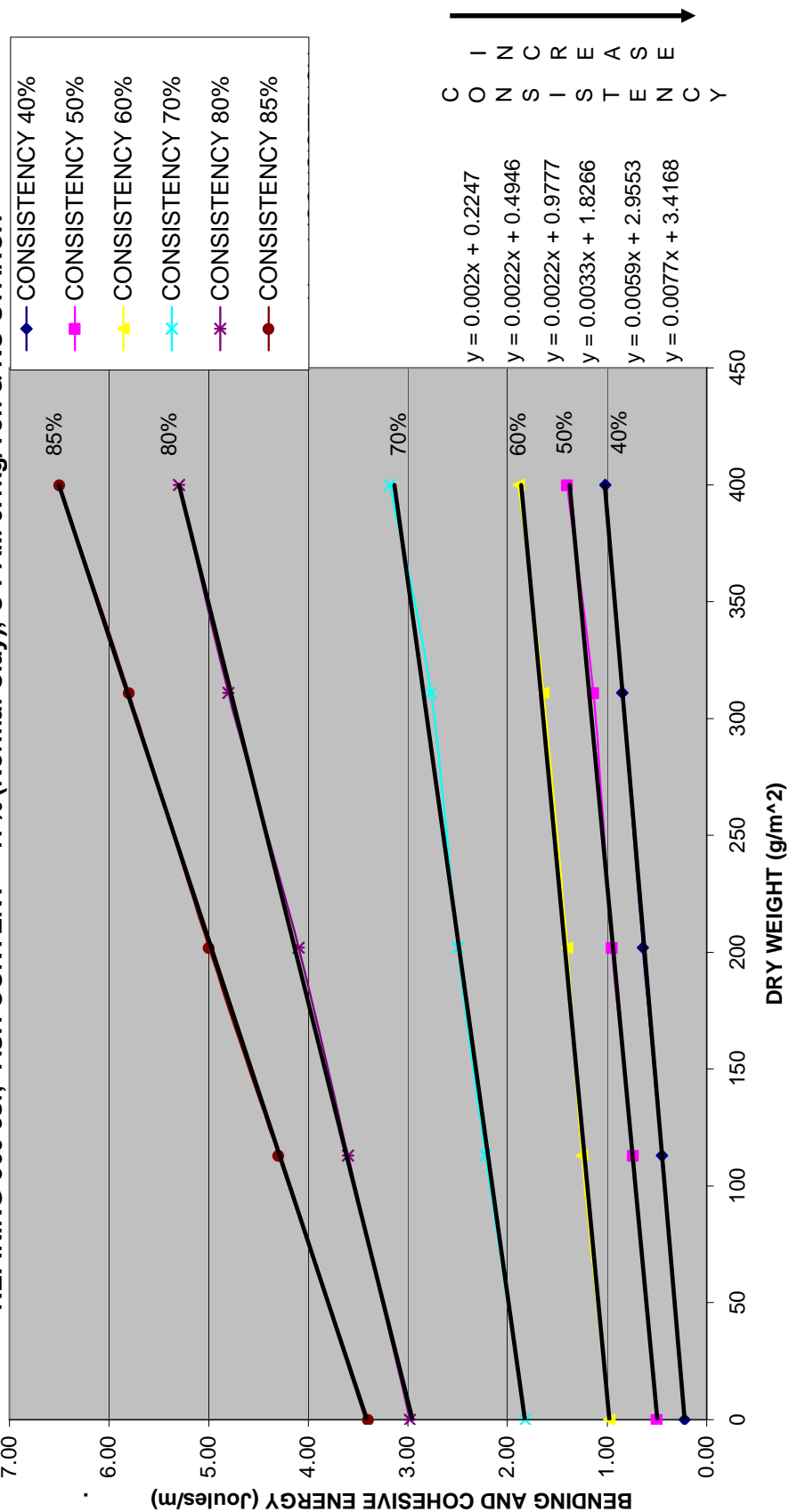
BENDING AND COHESIVE ENERGY Vs DRY WEIGHT
"Y" INTERSECTION CORRESPONDS TO THE COHESIVE ENERGY
CASE 2



BENDING AND COHESIVE ENERGY Vs DRY WEIGHT **"Y" INTERSECTION CORRESPONDS TO THE COHESIVE ENERGY**

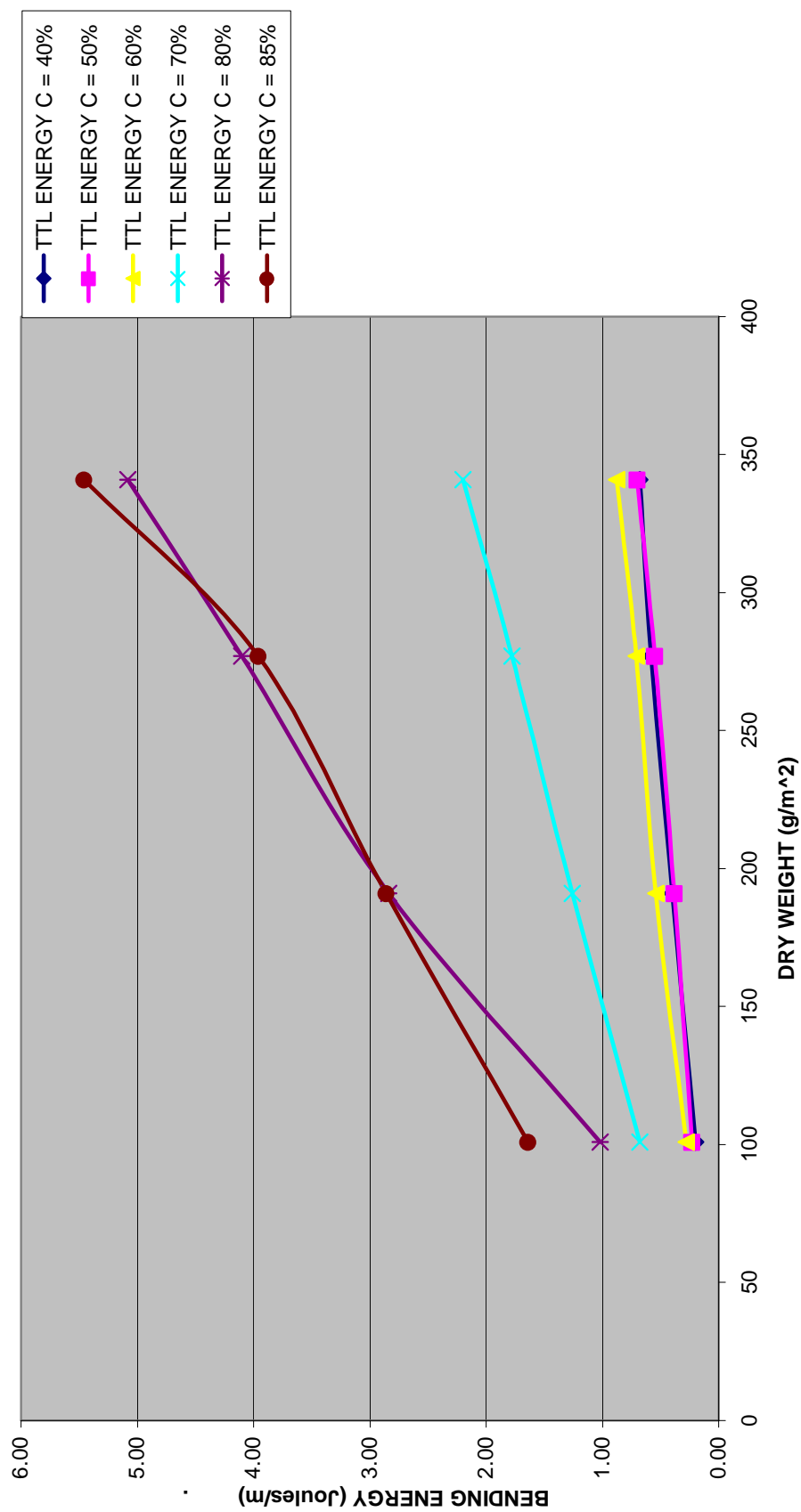
CASE 3

REFINING 560 csf; ASH CONTENT = 17% (Normal Clay), C-PAM 0.1kg/Ton & NO STARCH

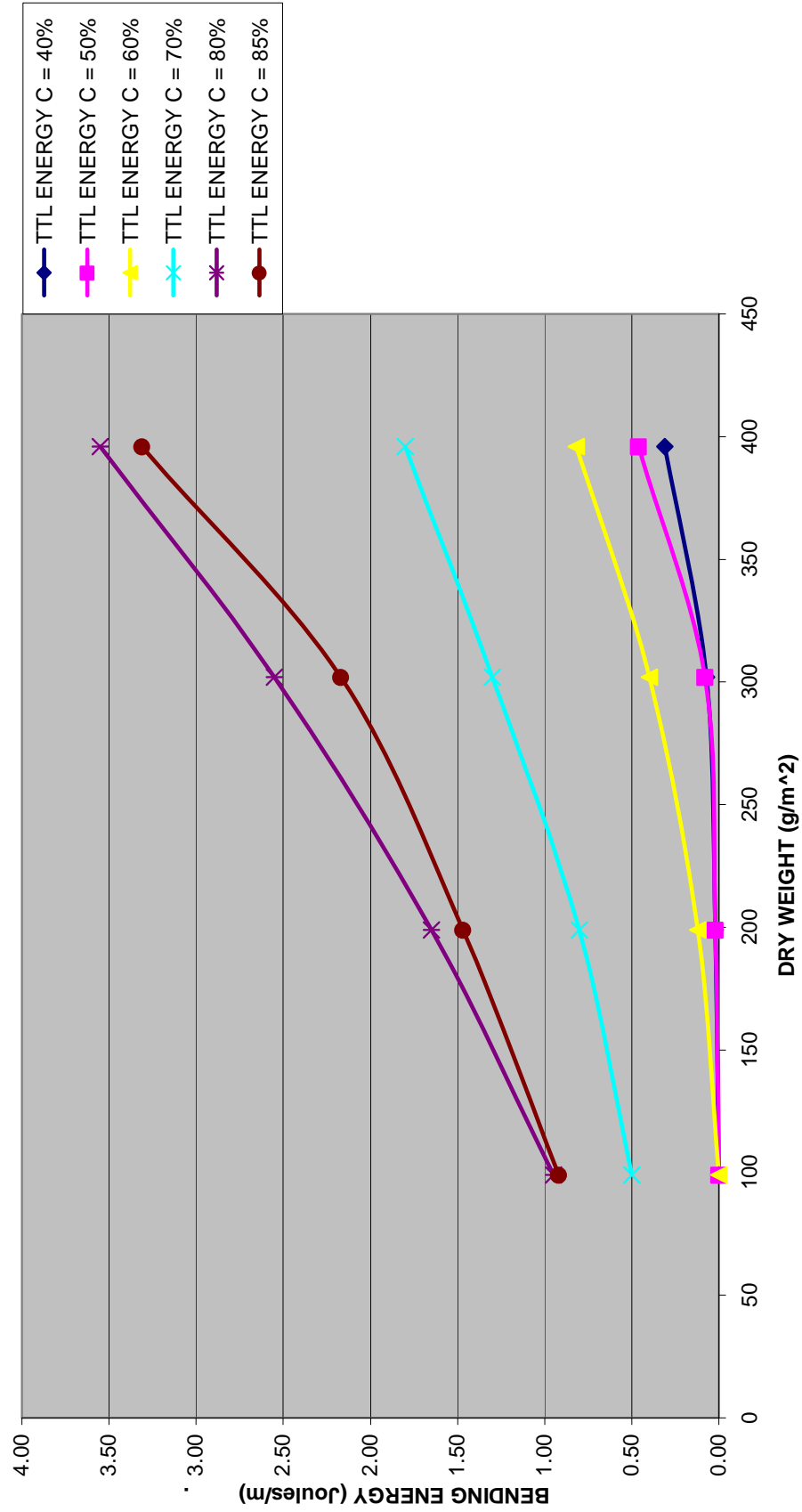


**APPENDIX A.4: BENDING ENERGY VS BASIS WEIGHT AT DIFFERENT
SOLIDS – CASES 1 TO 3**

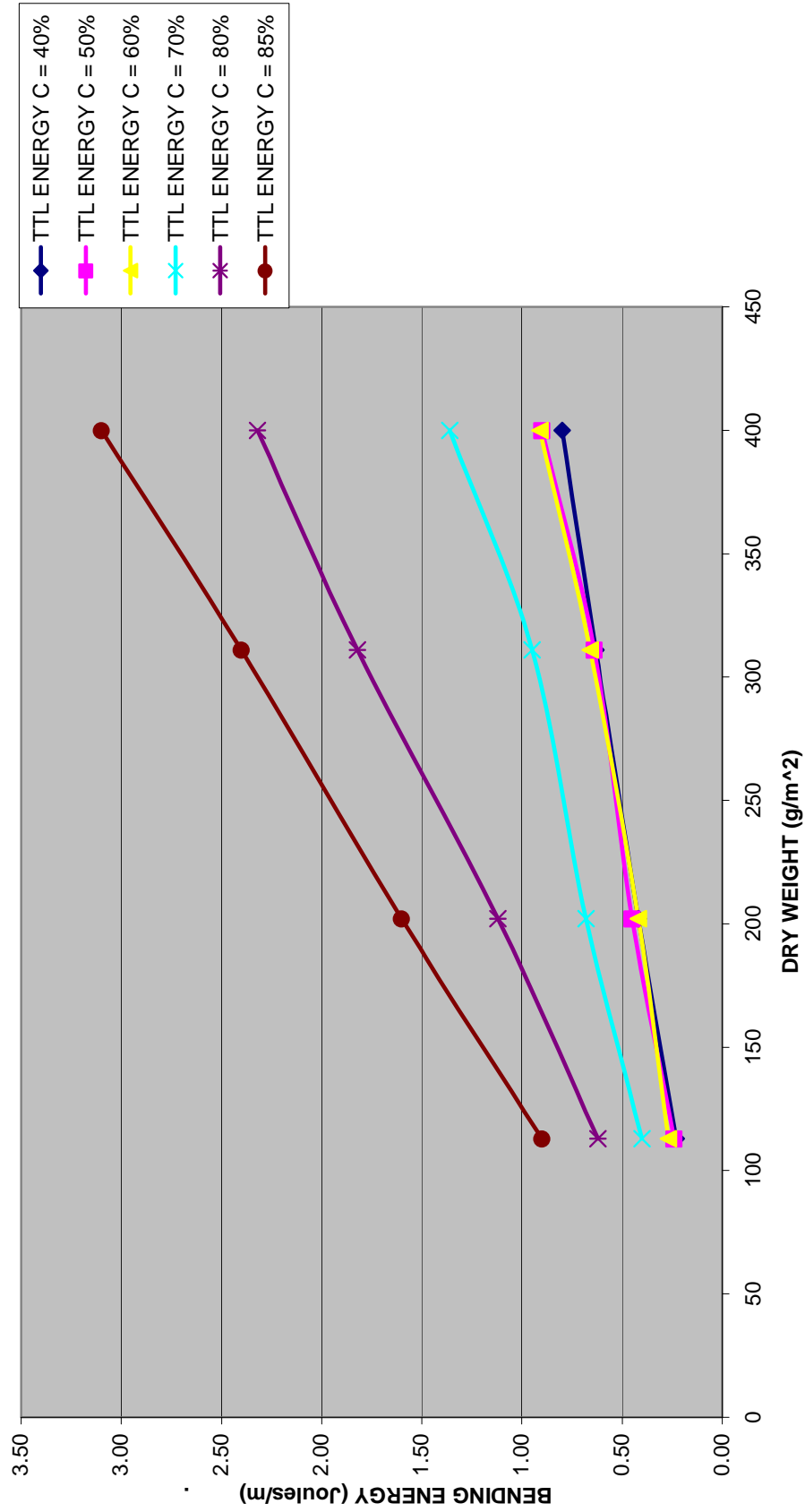
BENDING ENERGY Vs DRY WEIGHT
CASE 1
REFINING 560 csf; NO CHEMICALS



BENDING ENERGY Vs DRY WEIGHT
CASE 2
REFINING 740 csf; NO CHEMICALS



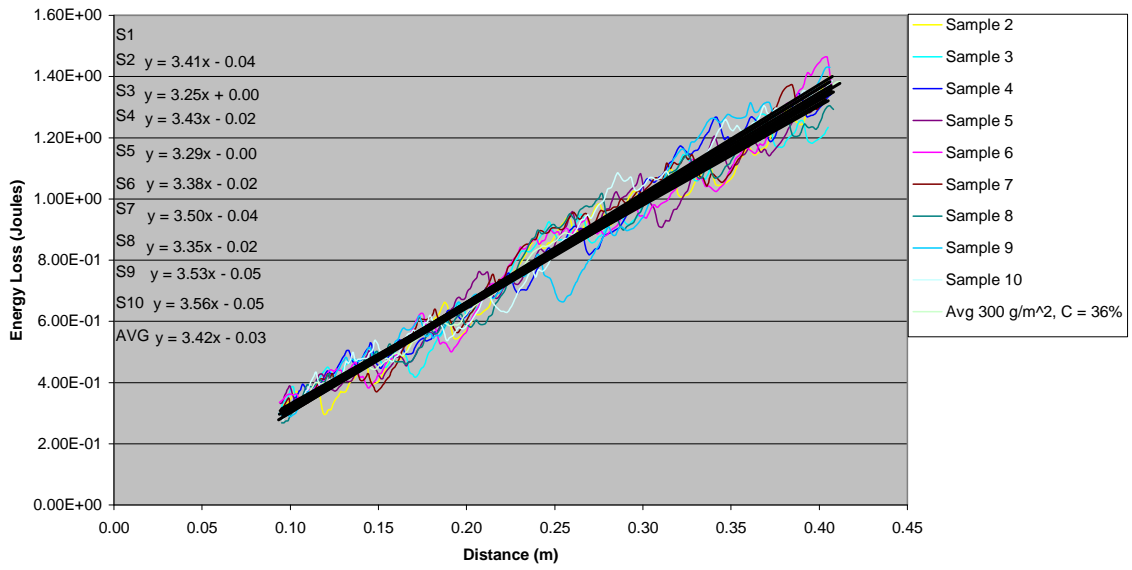
BENDING ENERGY Vs DRY WEIGHT
CASE 3
REFINING 560 csf; ASH CONTENT = 17% (Normal Clay), C-PAM 0.1kg/Ton & NO STARCH



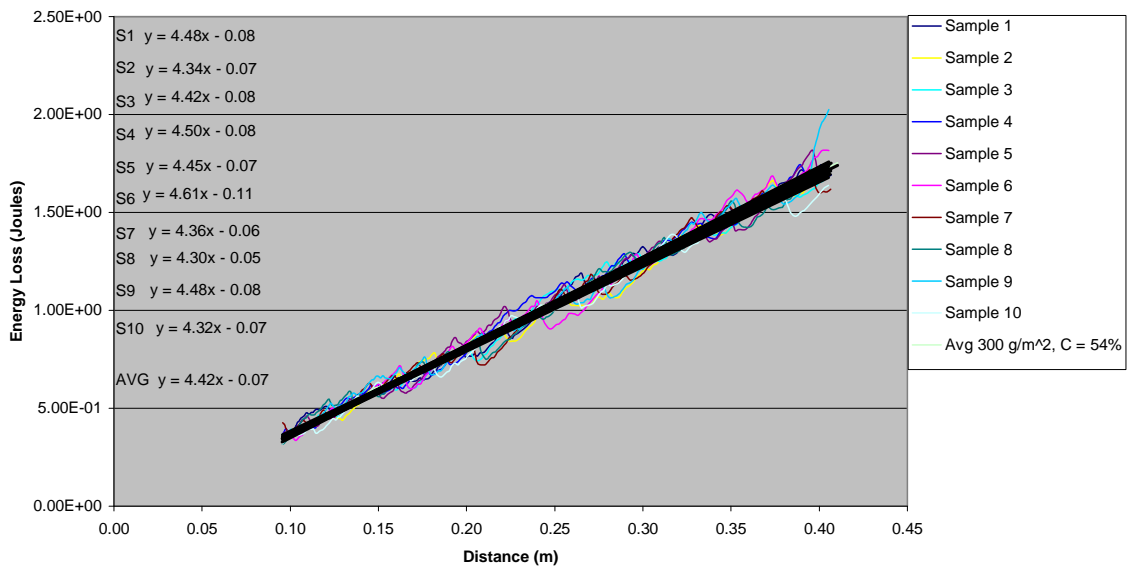
**APPENDIX B.1: APPARATUS ENERGY LOSS VS DISTANCE –
CASES 4 TO 12**

Case 4: Refining 440 C.S.F.; No Chemicals; Basis Weight 300 g/m²

REFINED 440 csf - 300 g/m²
 CONSISTENCY = 36 %
 SPLITTING WEIGHT 1100 gr

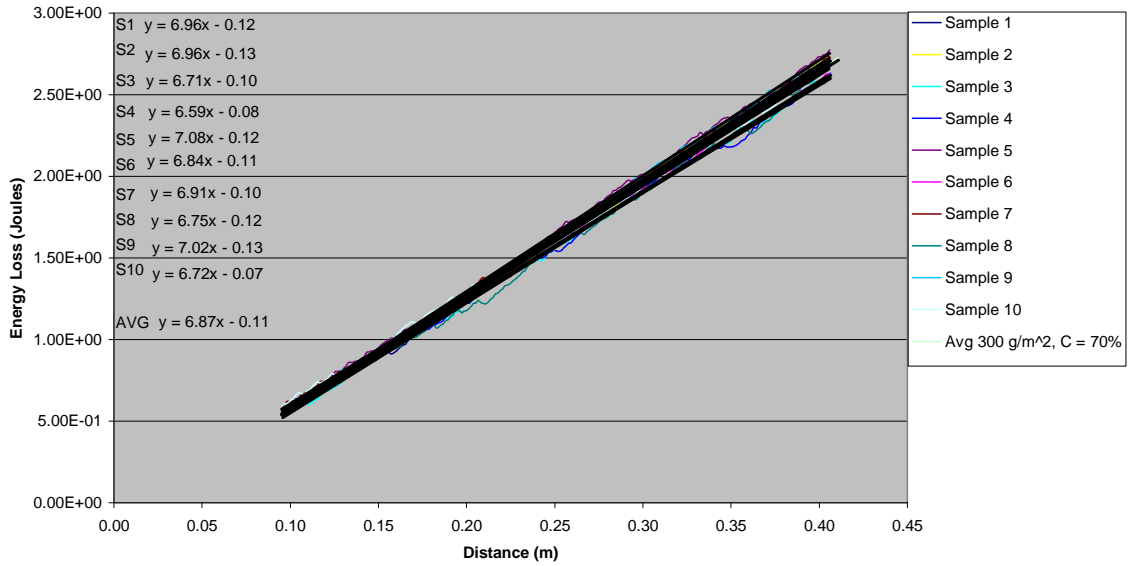


REFINED 440 csf - 300 g/m²
 CONSISTENCY = 54 %
 SPLITTING WEIGHT 1100 gr

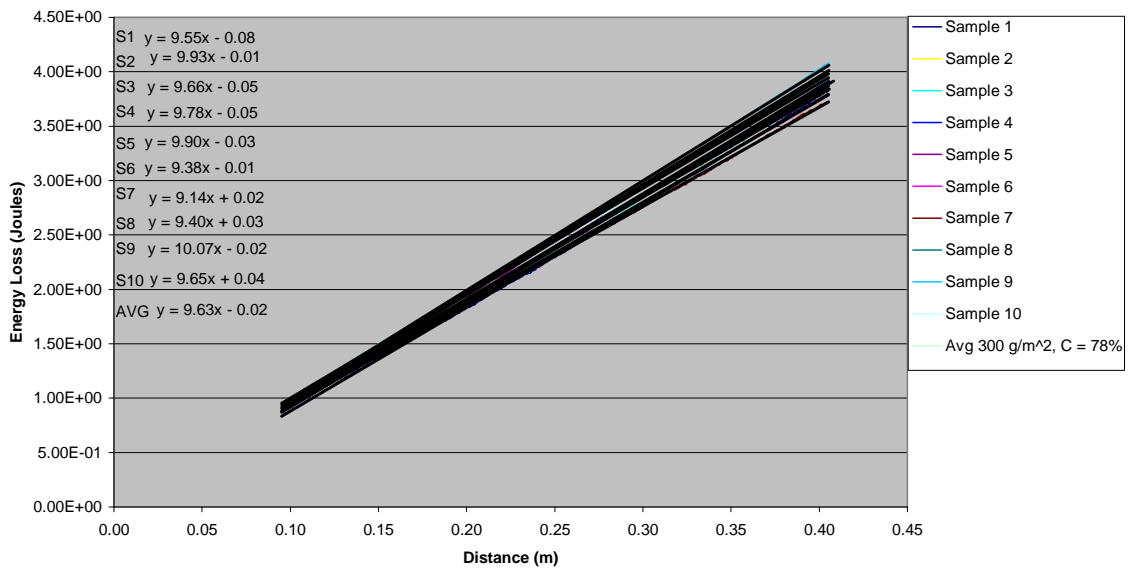


A

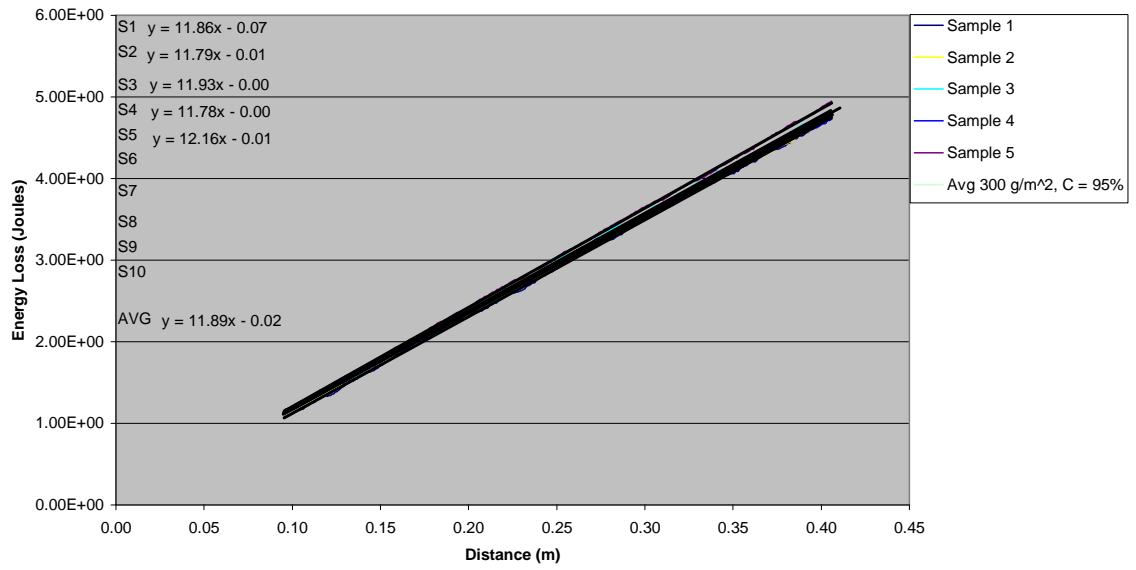
REFINED 440 csf - 300 g/m²
CONSISTENCY = 70 %
SPLITTING WEIGHT 1100 gr



REFINED 440 csf - 300 g/m²
CONSISTENCY = 78 %
SPLITTING WEIGHT 1100 gr

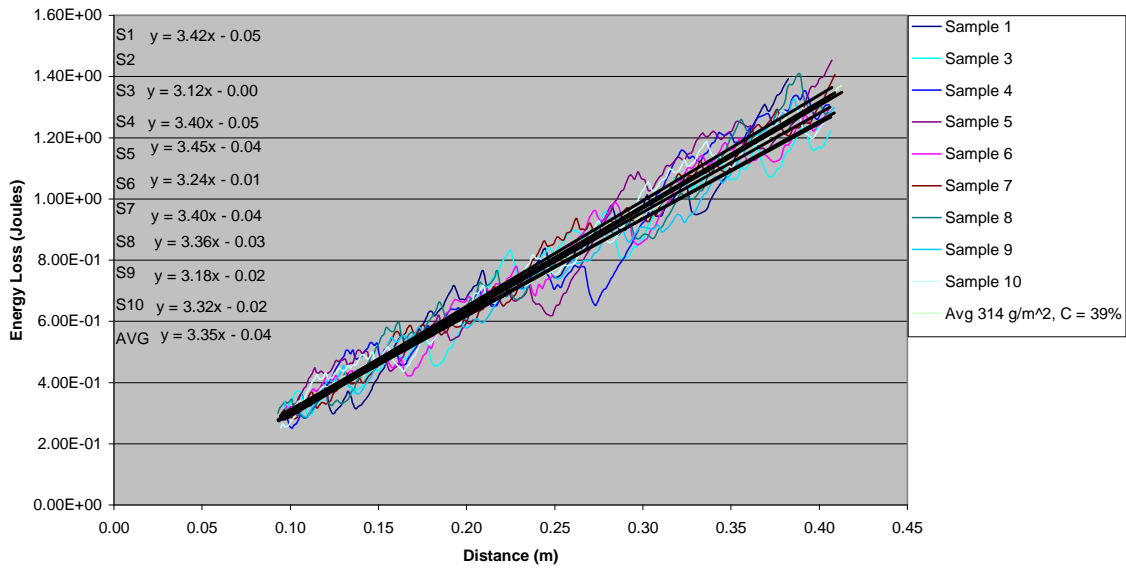


REFINED 440 csf - 300 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1540 gr

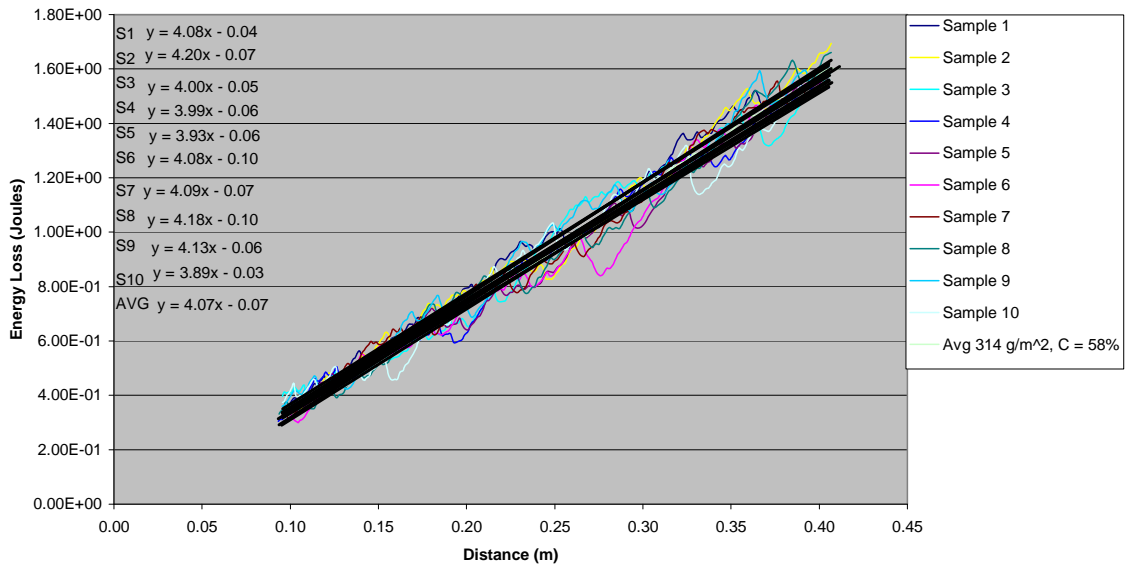


Case 5: Refining 560 C.S.F.; ASH 13% (Normal Clay), No Starch;
Basis Weight 314g/m²

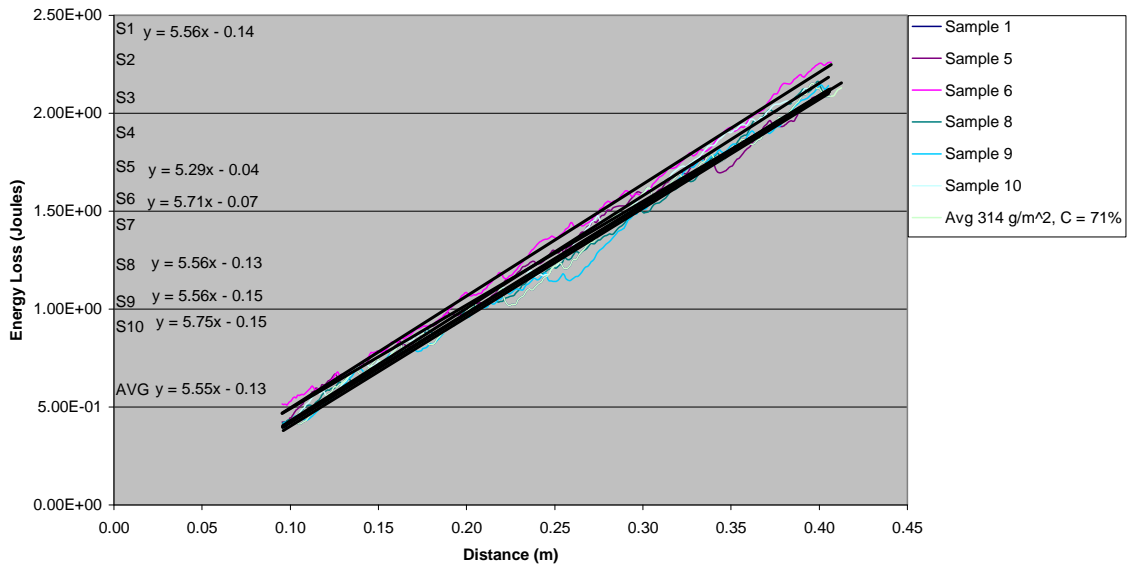
REFINED 560 csf / Ash = 13% - 314 g/m²
 CONSISTENCY = 39 %
 SPLITTING WEIGHT 1100 gr



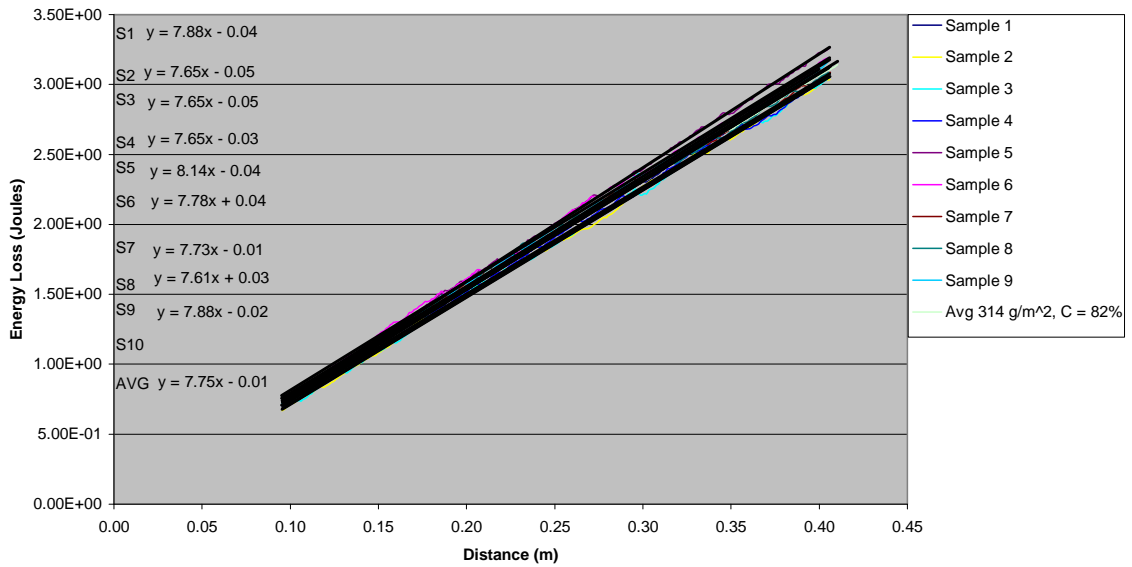
REFINED 560 csf / Ash = 13% - 314 g/m²
 CONSISTENCY = 58 %
 SPLITTING WEIGHT 1100 gr



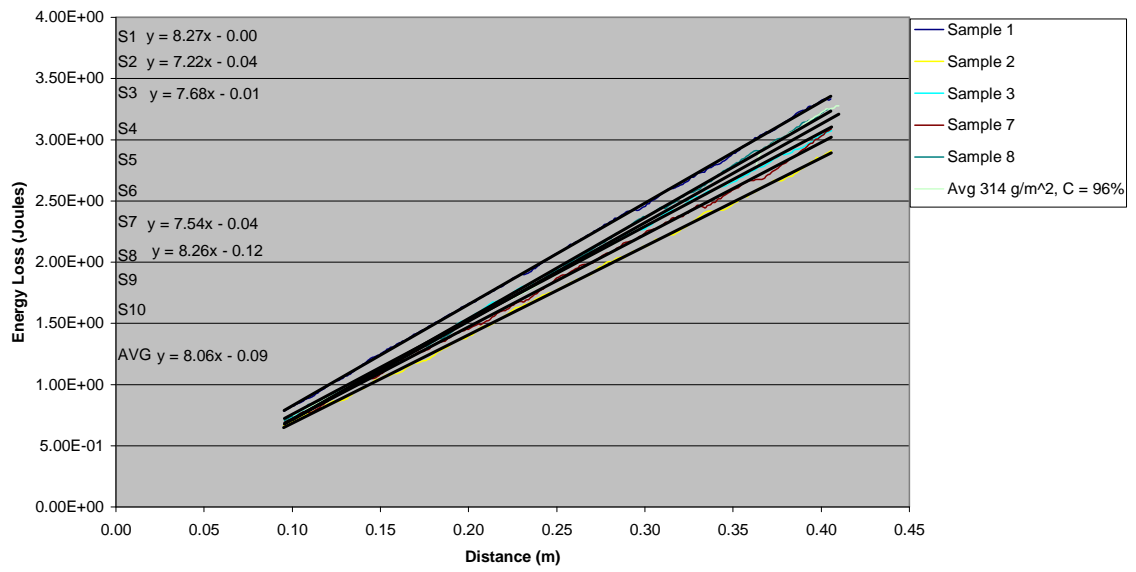
REFINED 560 csf / Ash = 13% - 314 g/m²
 CONSISTENCY = 71 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 13% - 314 g/m²
 CONSISTENCY = 82 %
 SPLITTING WEIGHT 1100 gr

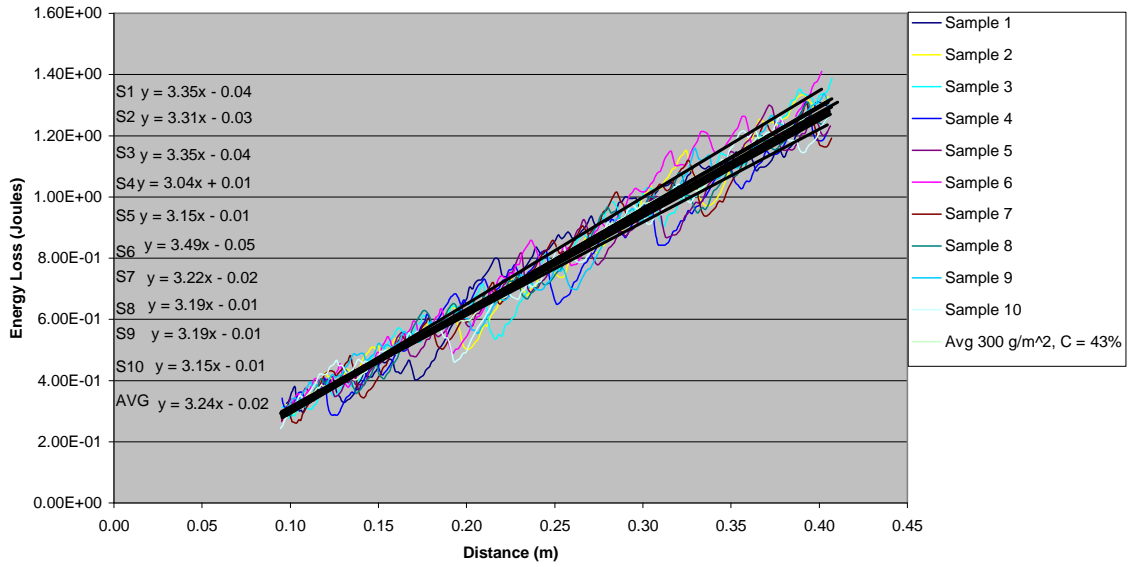


REFINED 560 csf / Ash = 13% - 314 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1100 gr

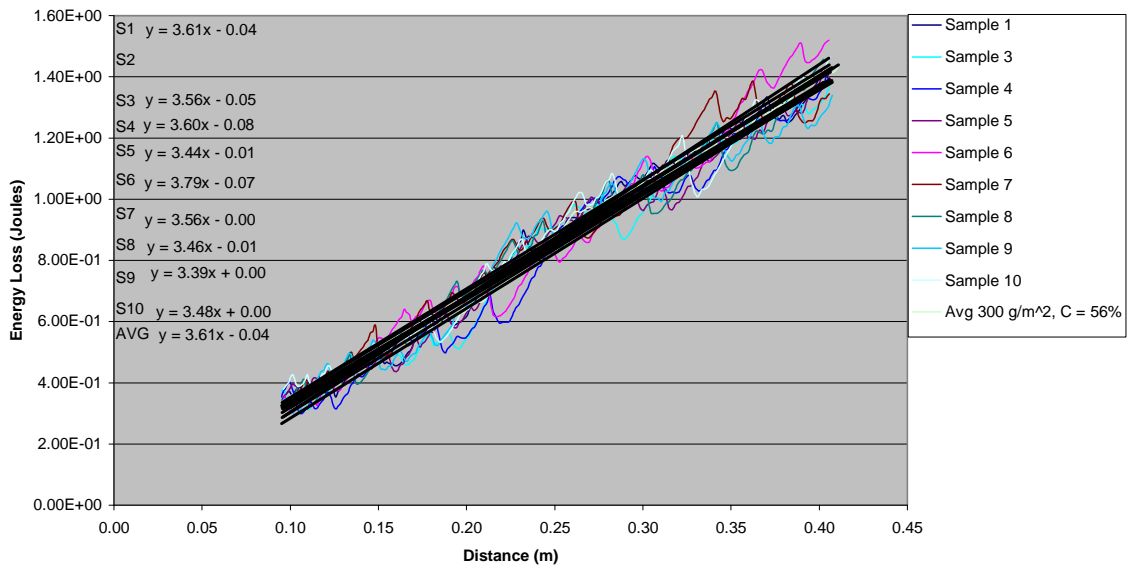


Case 6: Refining 560 C.S.F.; ASH 22% (Normal Clay), No Starch;
Basis Weight 305 g/m²

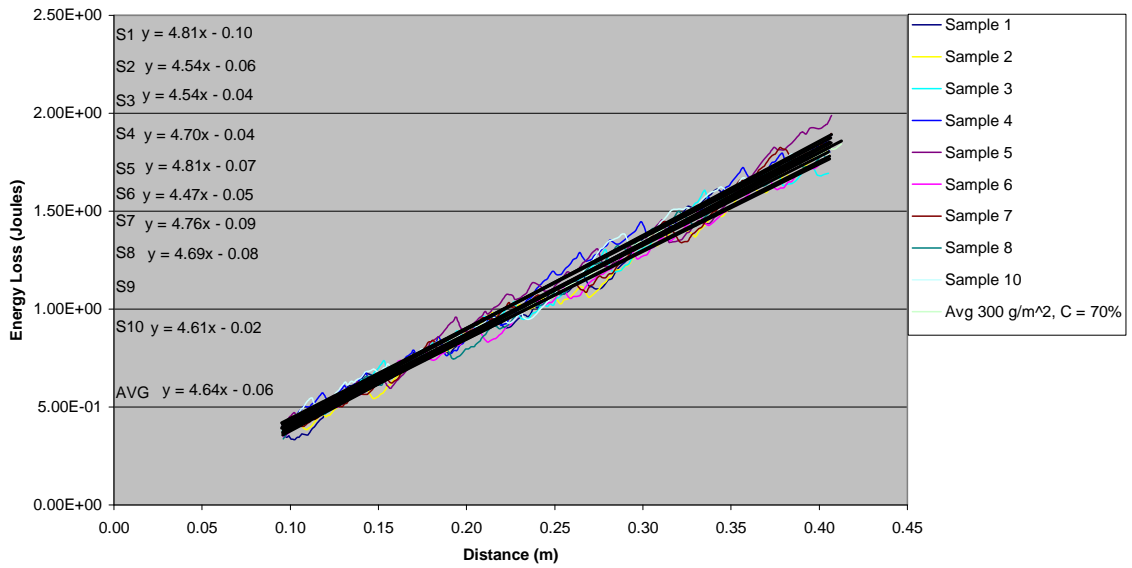
REFINED 560 csf / Ash = 22% - 300 g/m²
 CONSISTENCY = 43 %
 SPLITTING WEIGHT 1100 gr



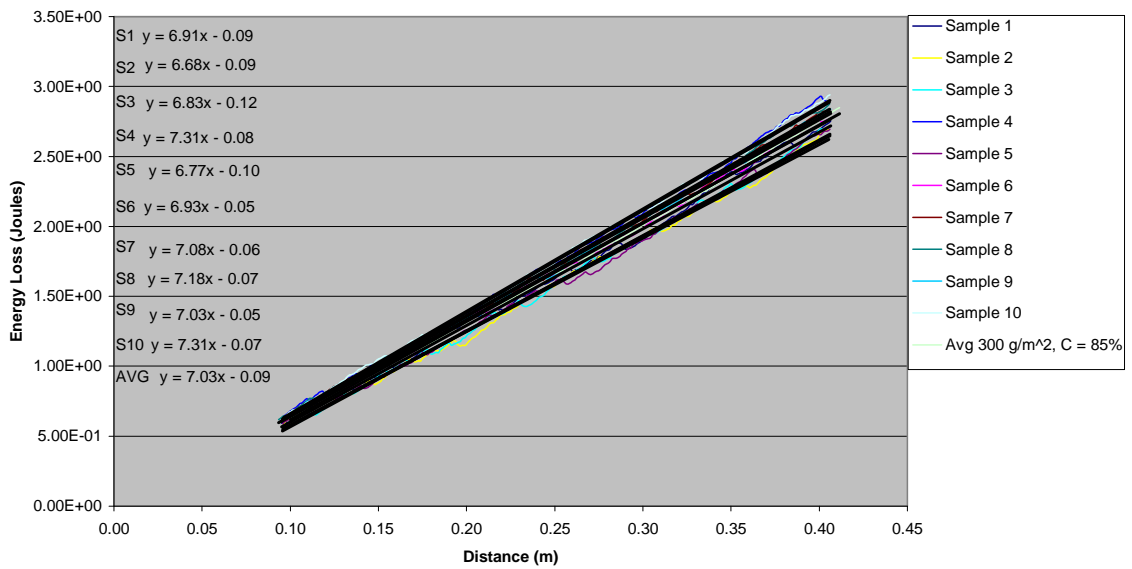
REFINED 560 csf / Ash = 22% - 300 g/m²
 CONSISTENCY = 56 %
 SPLITTING WEIGHT 1100 gr



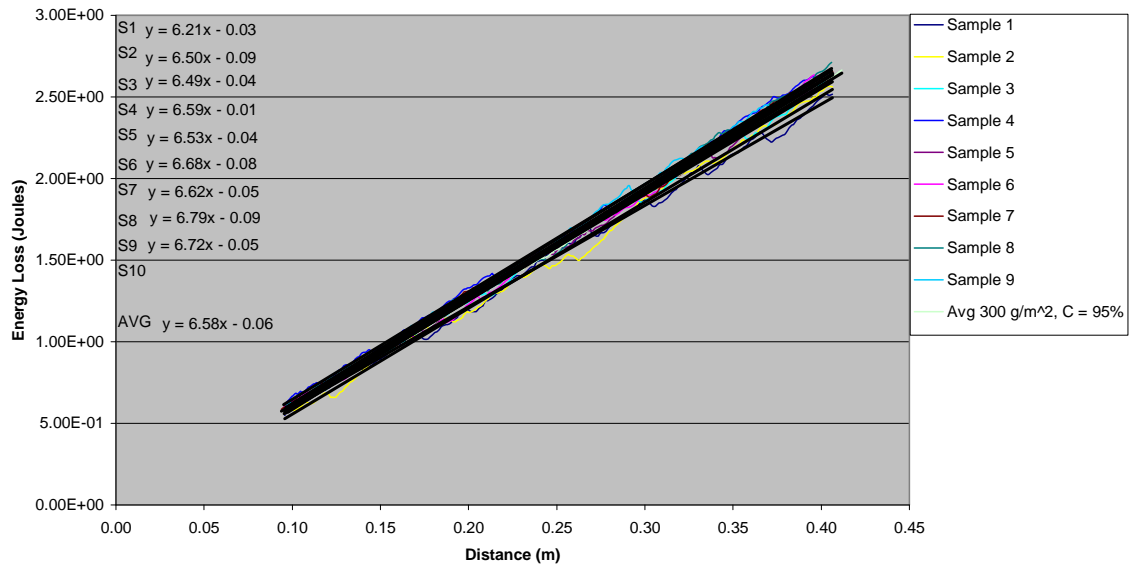
REFINED 560 csf / Ash = 22% - 300 g/m²
 CONSISTENCY = 70 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 22% - 300 g/m²
 CONSISTENCY = 85 %
 SPLITTING WEIGHT 1100 gr

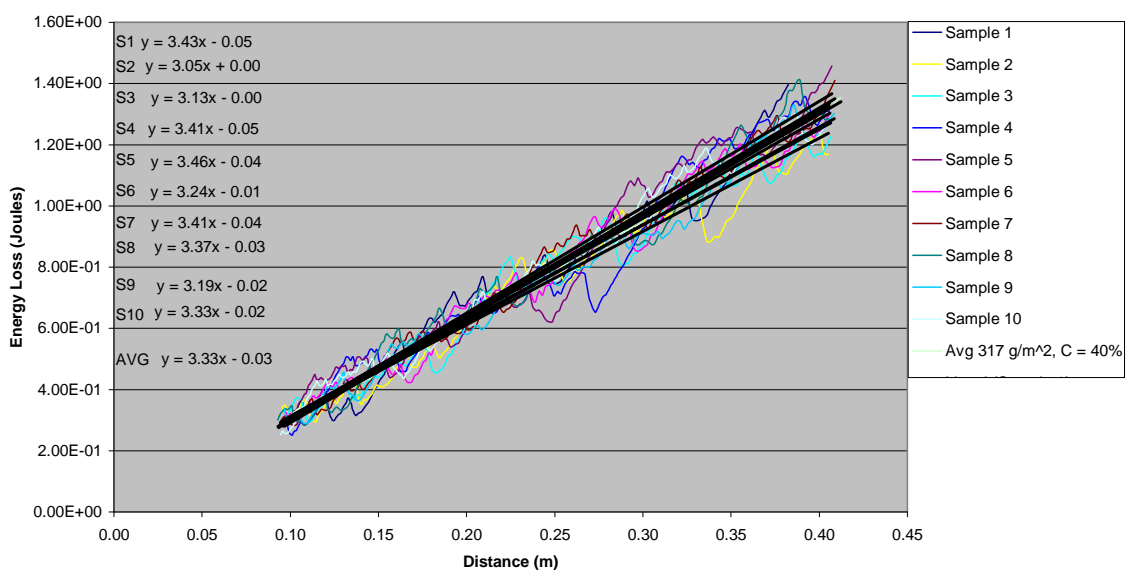


REFINED 560 csf / Ash = 22% - 300 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

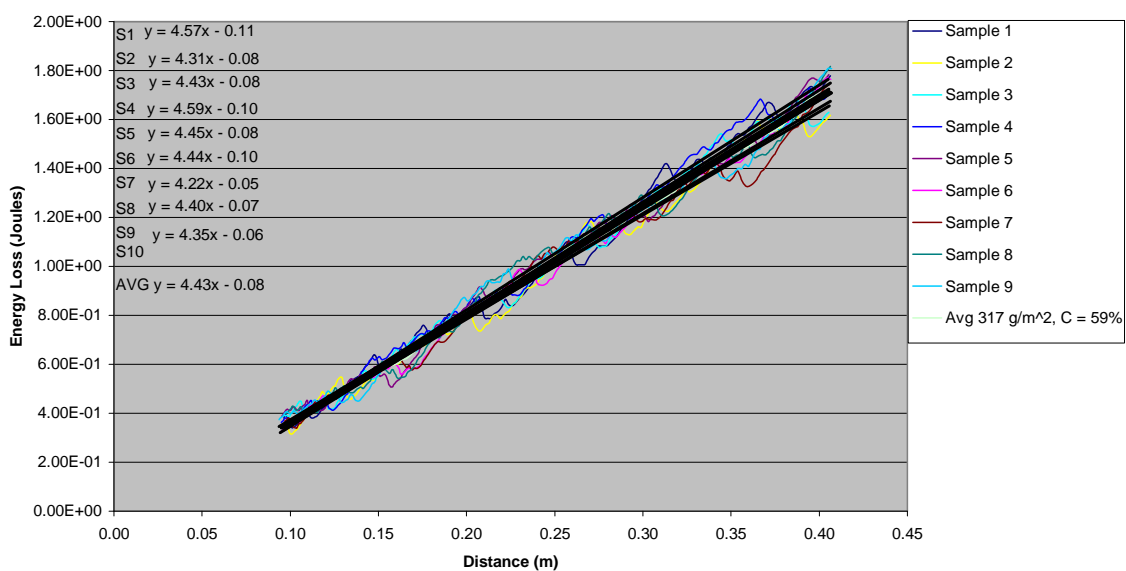


Case 7: Refining 560 C.S.F.; ASH 13% (Modified Clay), No Starch;
Basis Weight 317 g/m²

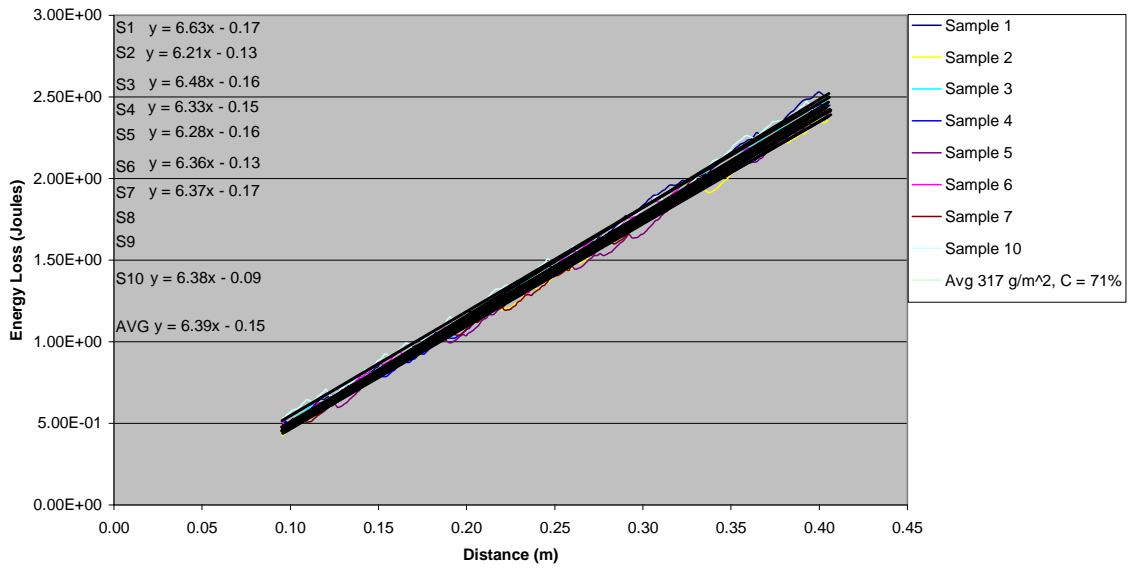
REFINED 560 csf / Ash = 13% (Modified Clay) - 317 g/m²
 CONSISTENCY = 40 %
 SPLITTING WEIGHT 1100 gr



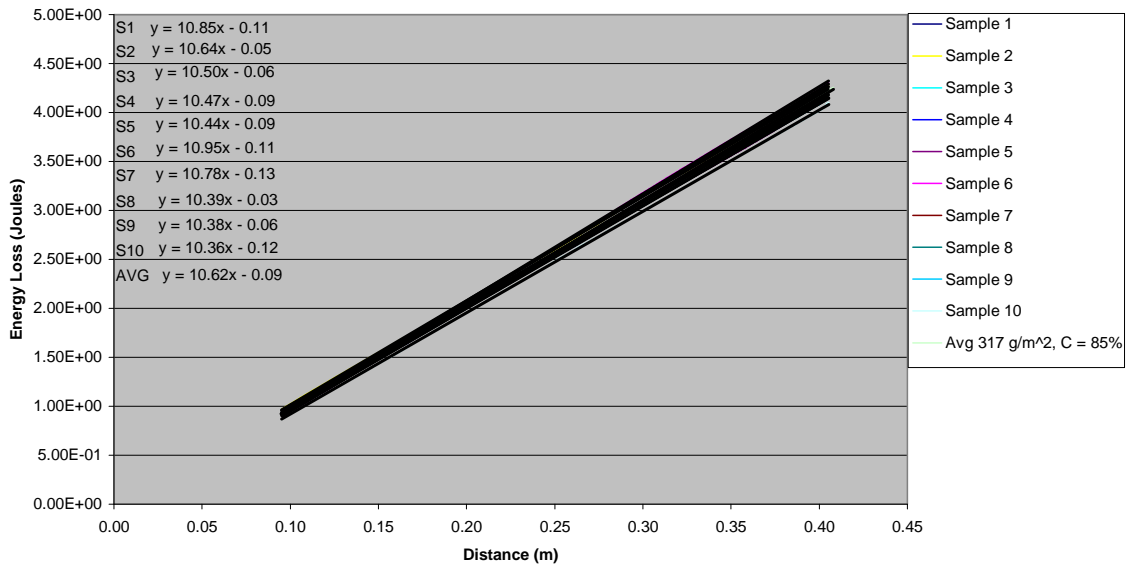
REFINED 560 csf / Ash = 13% (Modified Clay) - 317 g/m²
 CONSISTENCY = 59 %
 SPLITTING WEIGHT 1100 gr



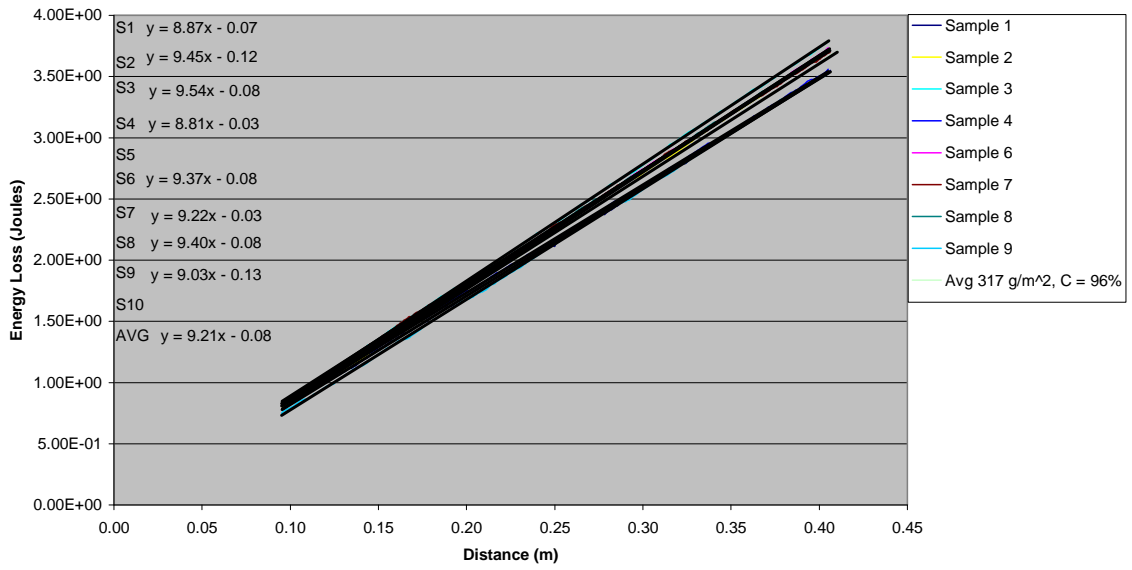
REFINED 560 csf / Ash = 13% (Modified Clay) - 317 g/m²
 CONSISTENCY = 71 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 13% (Modified Clay) - 317 g/m²
 CONSISTENCY = 85 %
 SPLITTING WEIGHT 1100 gr

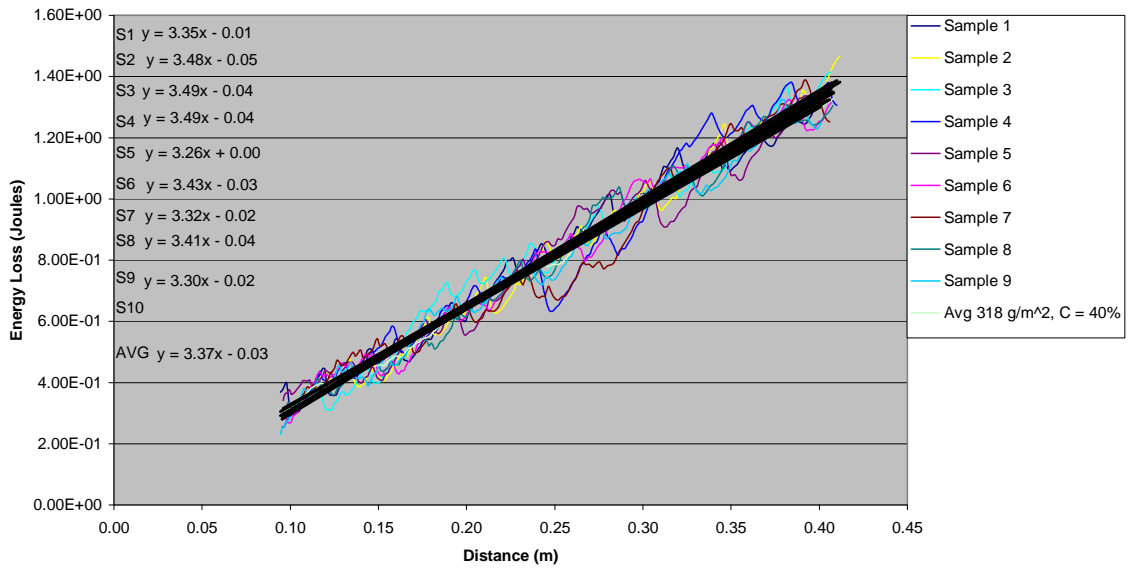


REFINED 560 csf / Ash = 13% (Modified Clay) - 317 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1100 gr

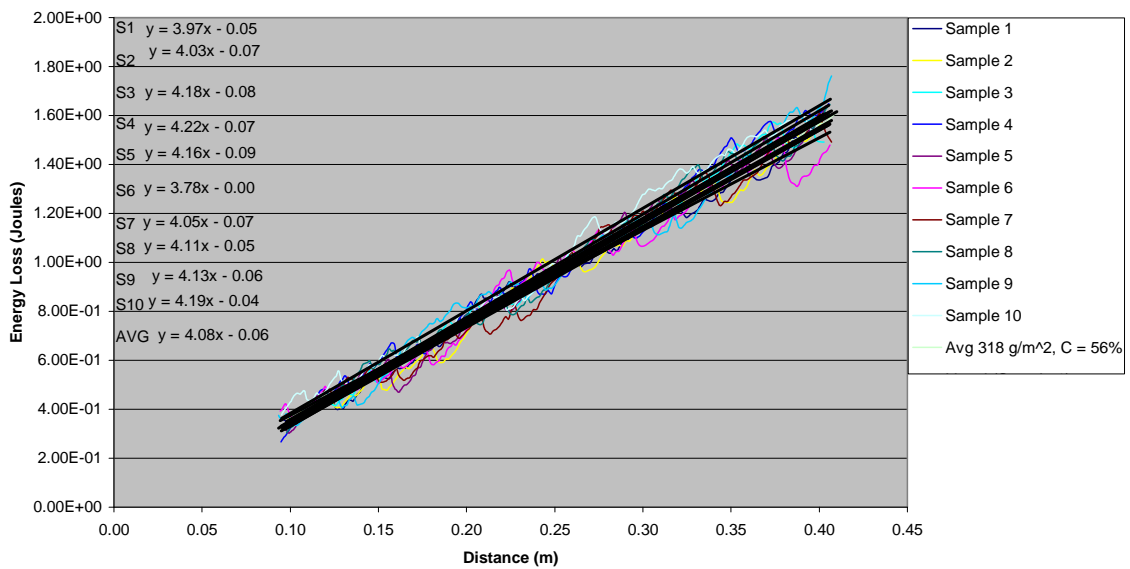


Case 8: Refining 560 C.S.F.; ASH 18% (Modified Clay), No Starch;
Basis Weight 318 g/m²

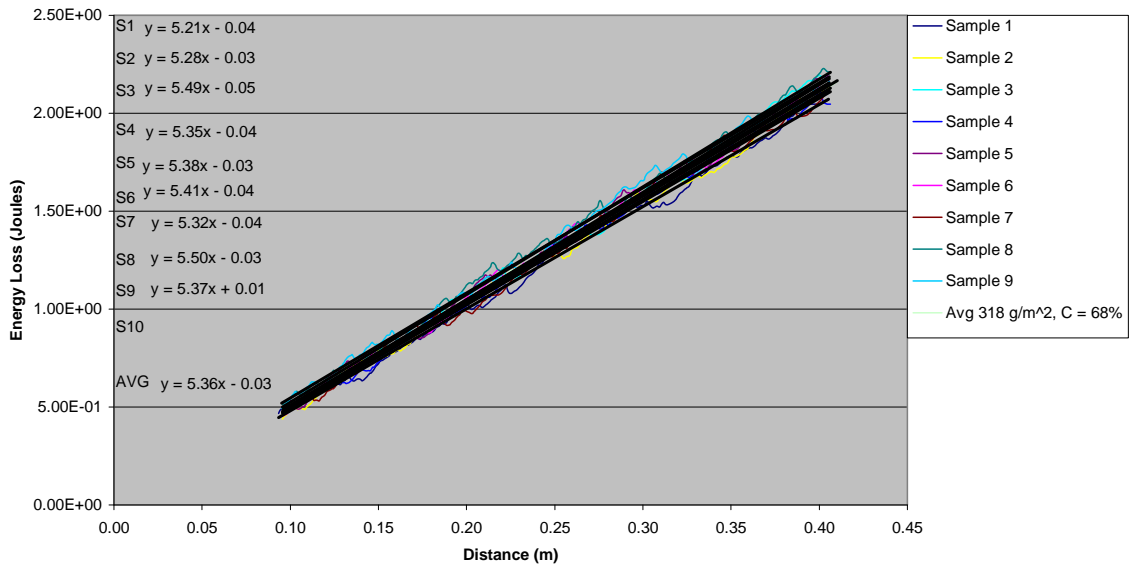
REFINED 560 csf / Ash = 18% (Modified Clay) - 318 g/m²
CONSISTENCY = 40 %
SPLITTING WEIGHT 1100 gr



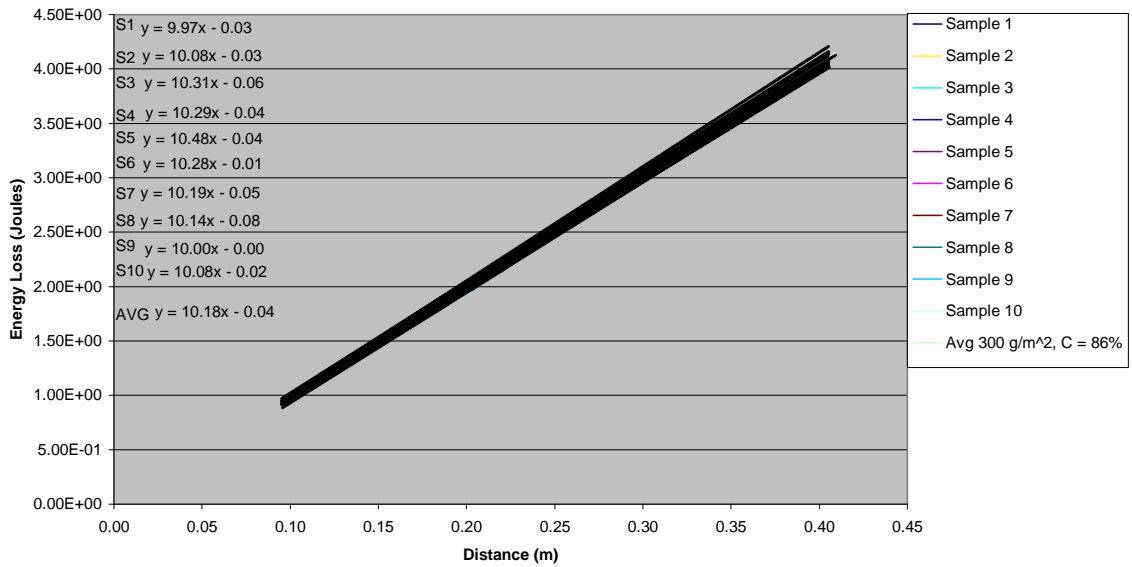
REFINED 560 csf / Ash = 18% (Modified Clay) - 318 g/m²
CONSISTENCY = 56 %
SPLITTING WEIGHT 1100 gr



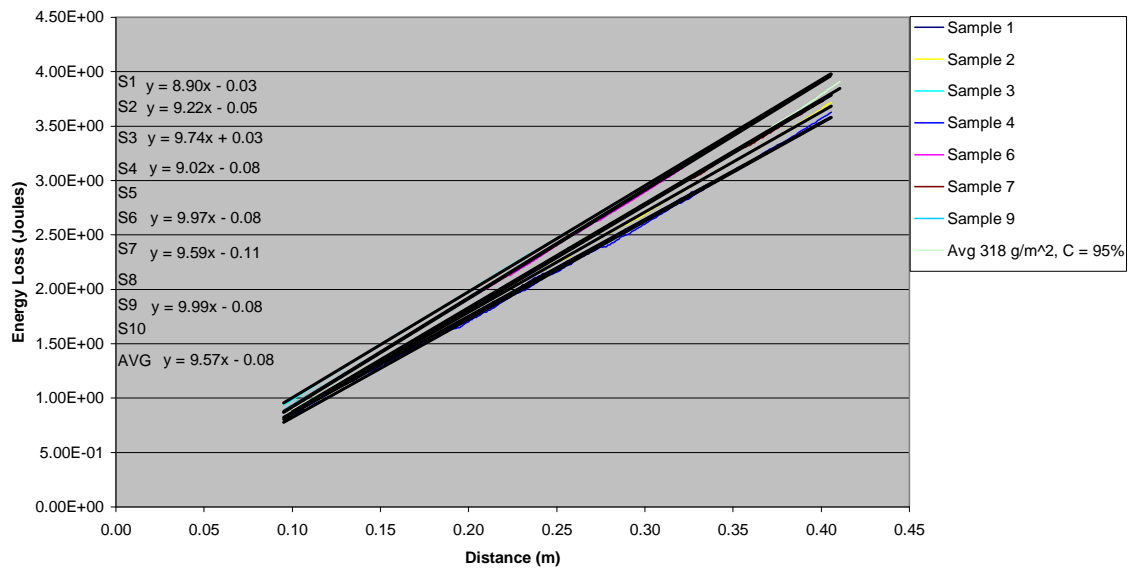
REFINED 560 csf / Ash = 18% (Modified Clay) - 318 g/m²
CONSISTENCY = 68 %
SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 18% (Modified Clay) - 318 g/m²
CONSISTENCY = 86 %
SPLITTING WEIGHT 1100 gr

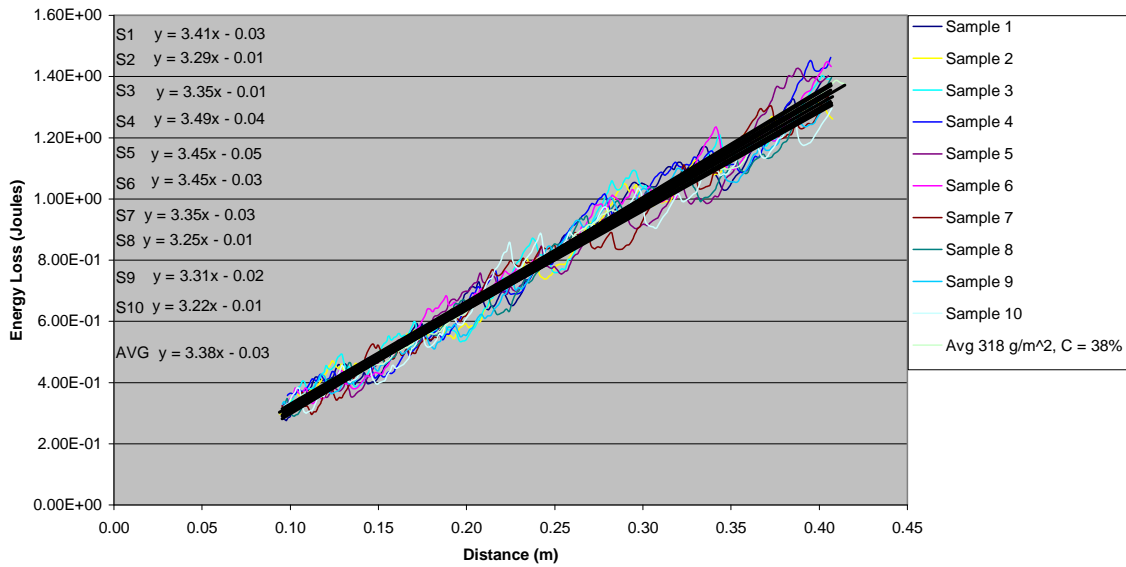


REFINED 560 csf / Ash = 18% (Modified Clay) - 318 g/m²
 CONSISTENCY = 95 %
 SPLITTING WEIGHT 1100 gr

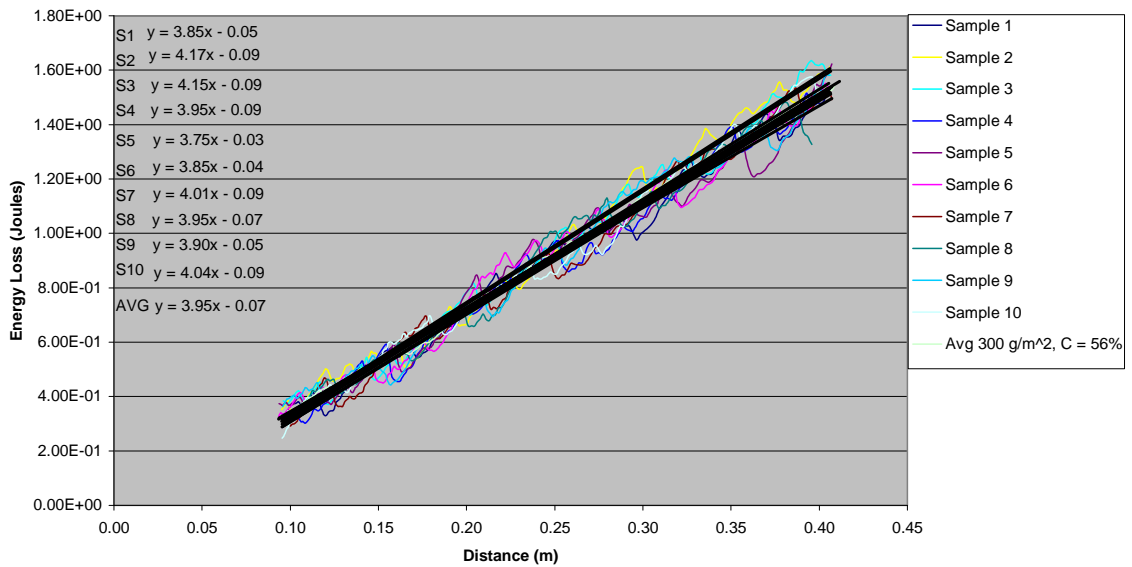


Case 9: Refining 560 C.S.F.; ASH 24% (Modified Clay), No Starch;
Basis Weight 318 g/m²

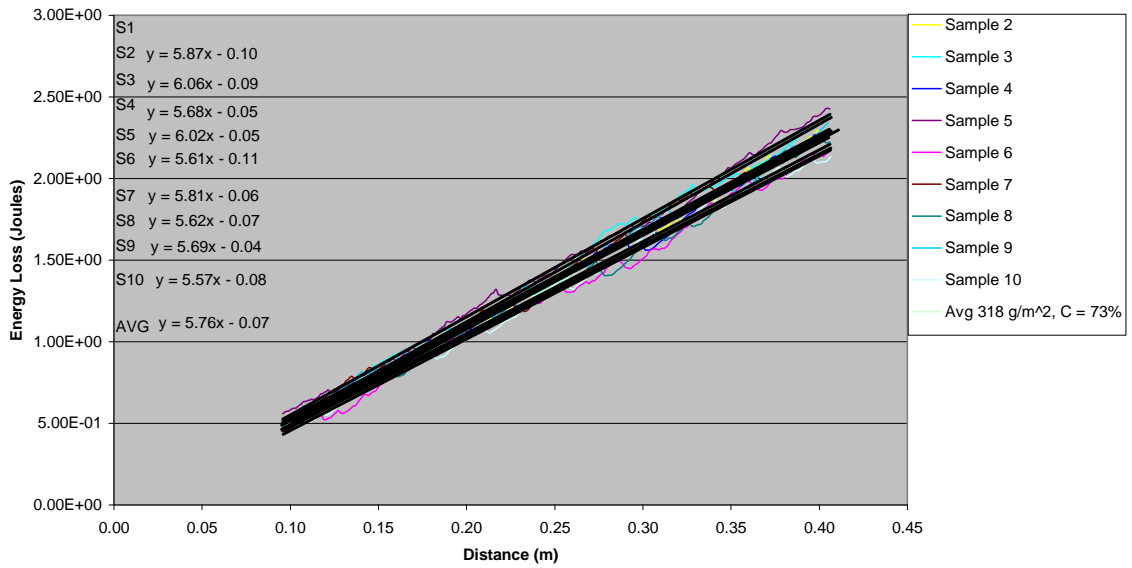
REFINED 560 csf / Ash = 24% (Modified Clay) - 318 g/m²
 CONSISTENCY = 38 %
 SPLITTING WEIGHT 1100 gr



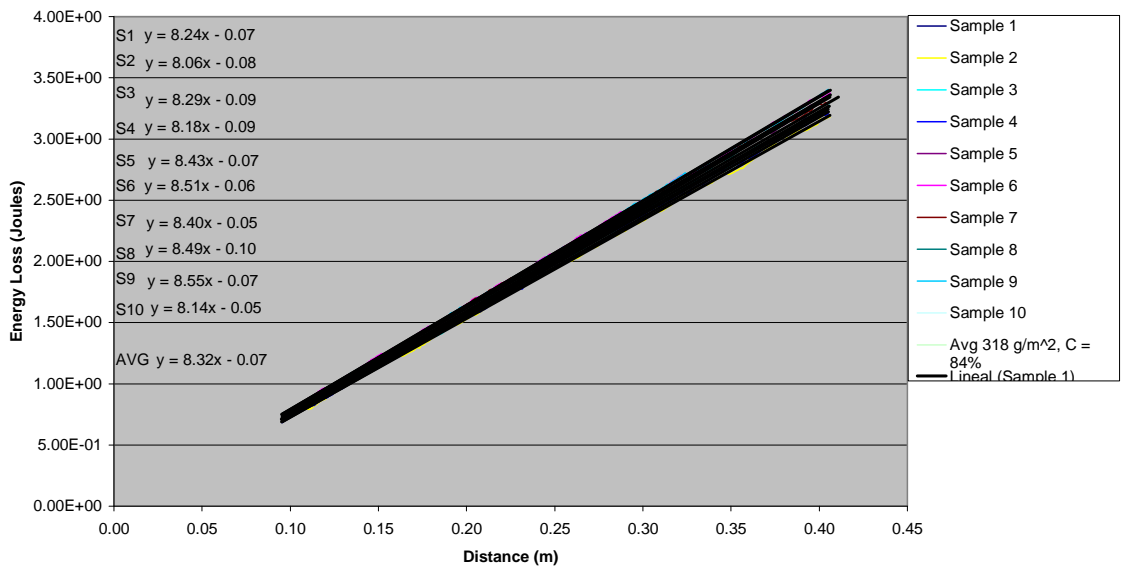
REFINED 560 csf / Ash = 24% (Modified Clay) - 318 g/m²
 CONSISTENCY = 56 %
 SPLITTING WEIGHT 1100 gr



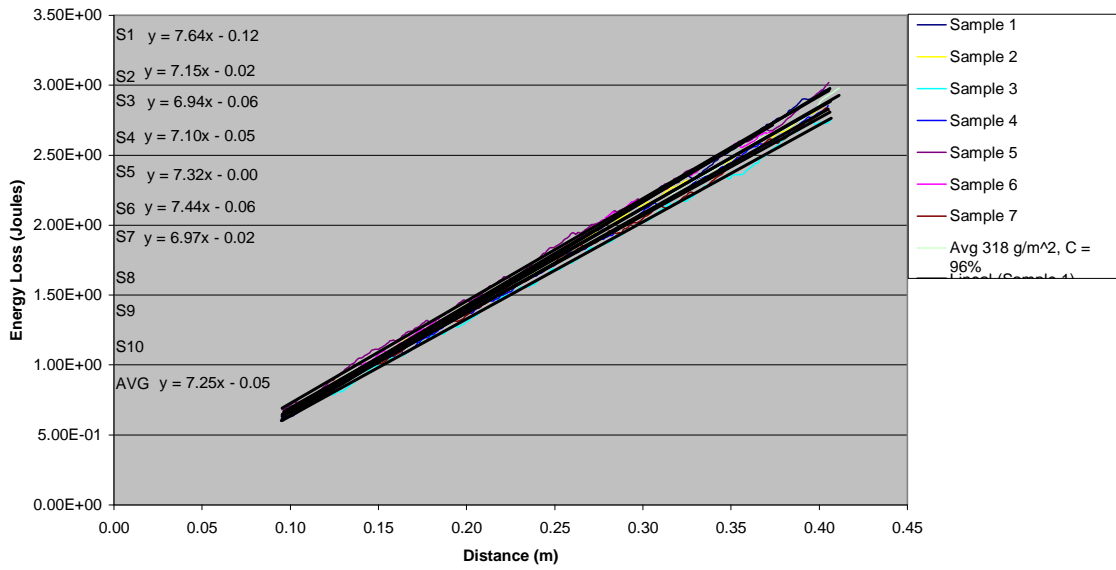
REFINED 560 csf / Ash = 24% (Modified Clay) - 318 g/m²
 CONSISTENCY = 73 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 24% (Modified Clay) - 318 g/m²
 CONSISTENCY = 84 %
 SPLITTING WEIGHT 1100 gr

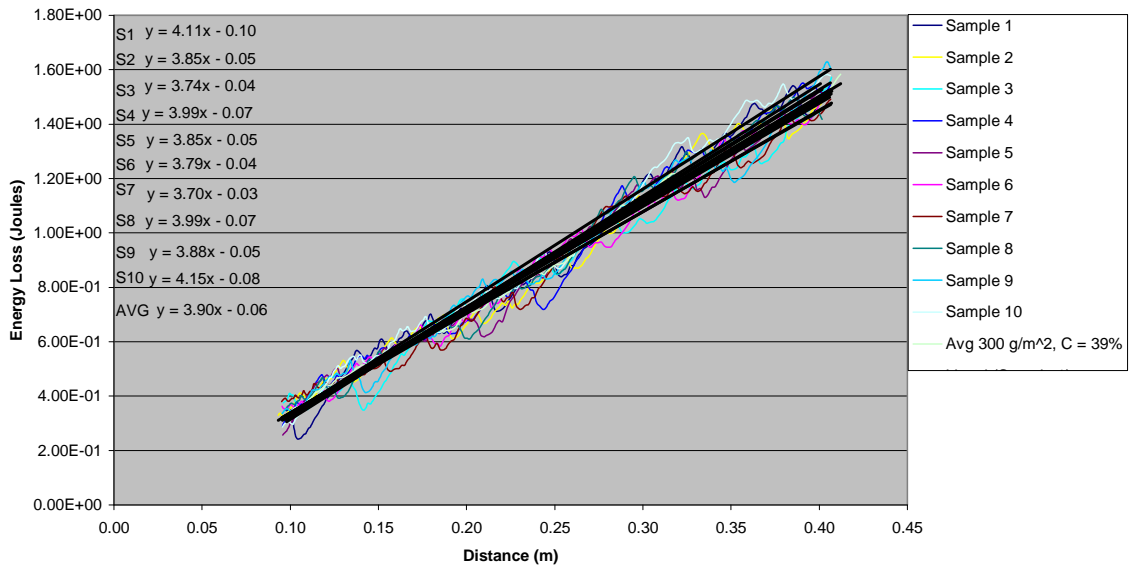


REFINED 560 csf / Ash = 24% (Modified Clay) - 318 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1100 gr

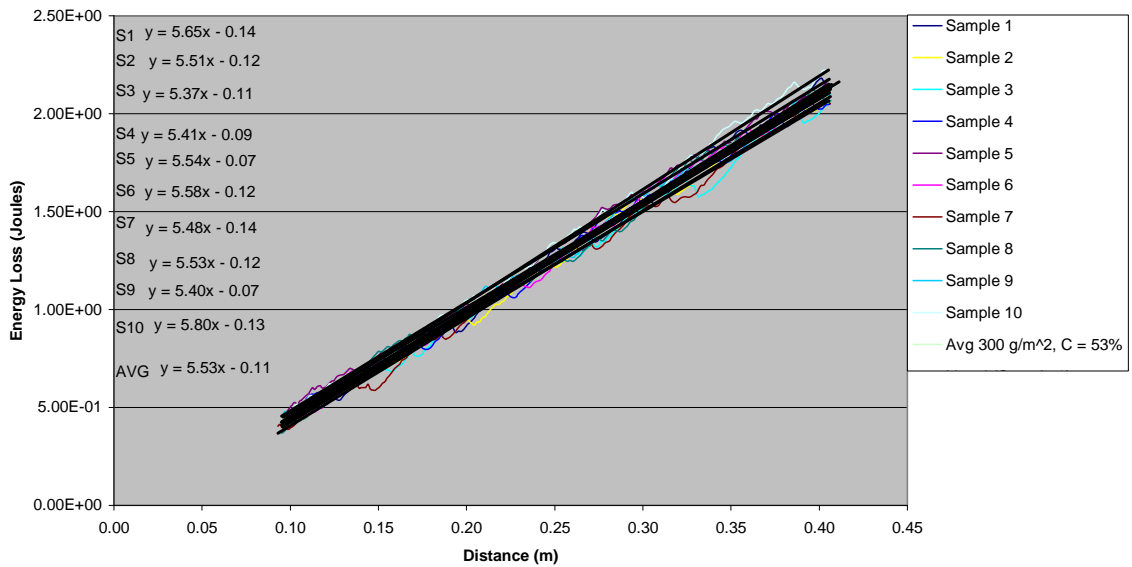


Case 10: Refining 560 C.S.F.; 15 kg/ton C-Starch, No Clay; Basis Weight 303
g/m²

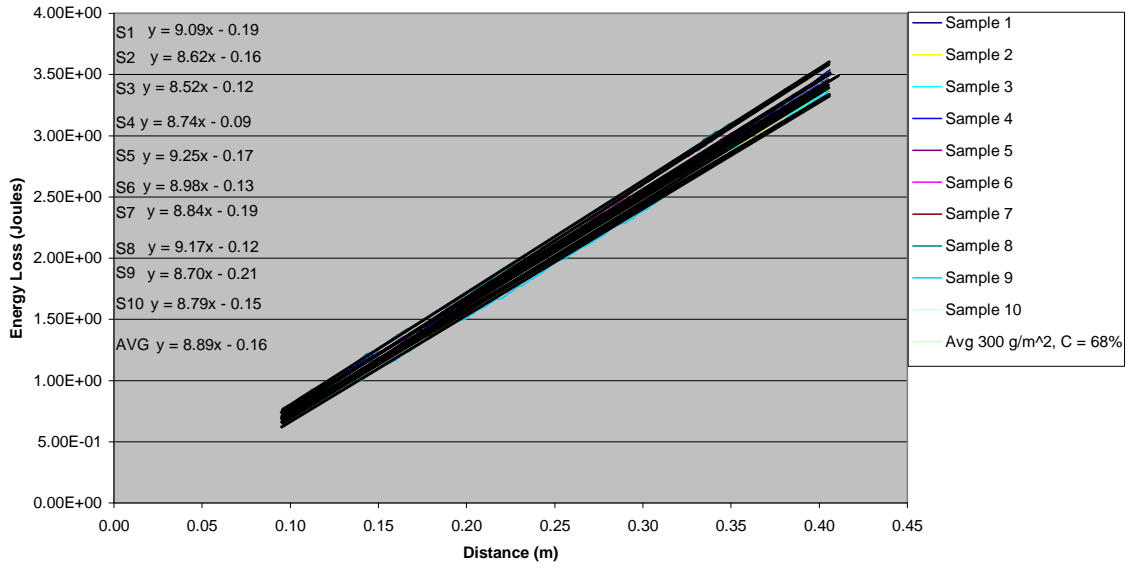
REFINED 560 csf + CATIONIC STARCH (15 Kg/Ton) - 300 g/m²
CONSISTENCY = 39 %
SPLITTING WEIGHT 1100 gr



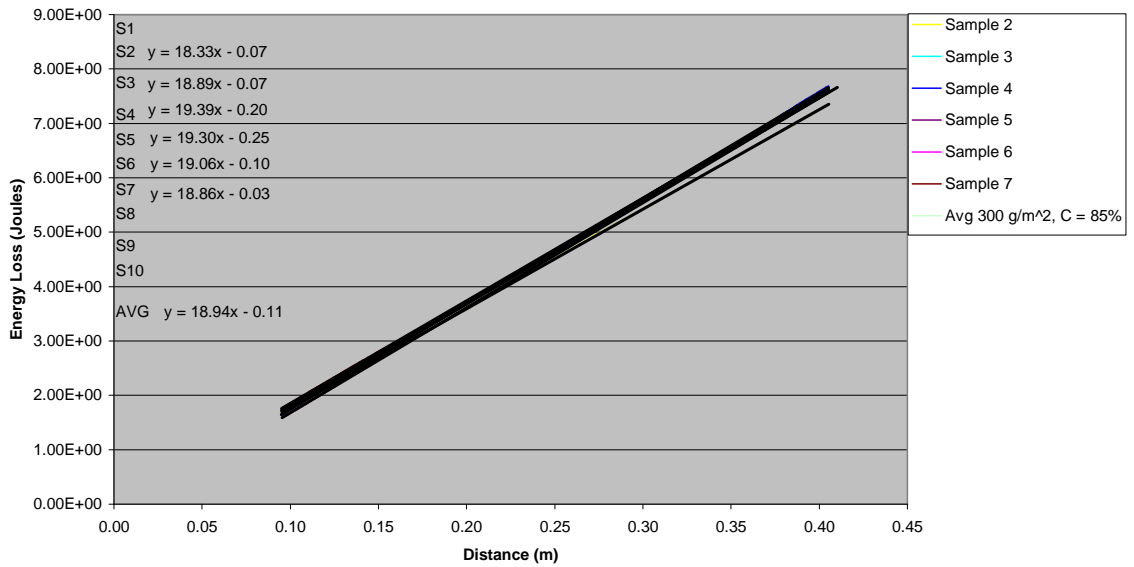
REFINED 560 csf + CATIONIC STARCH (15 Kg/Ton) - 300 g/m²
CONSISTENCY = 53 %
SPLITTING WEIGHT 1100 gr



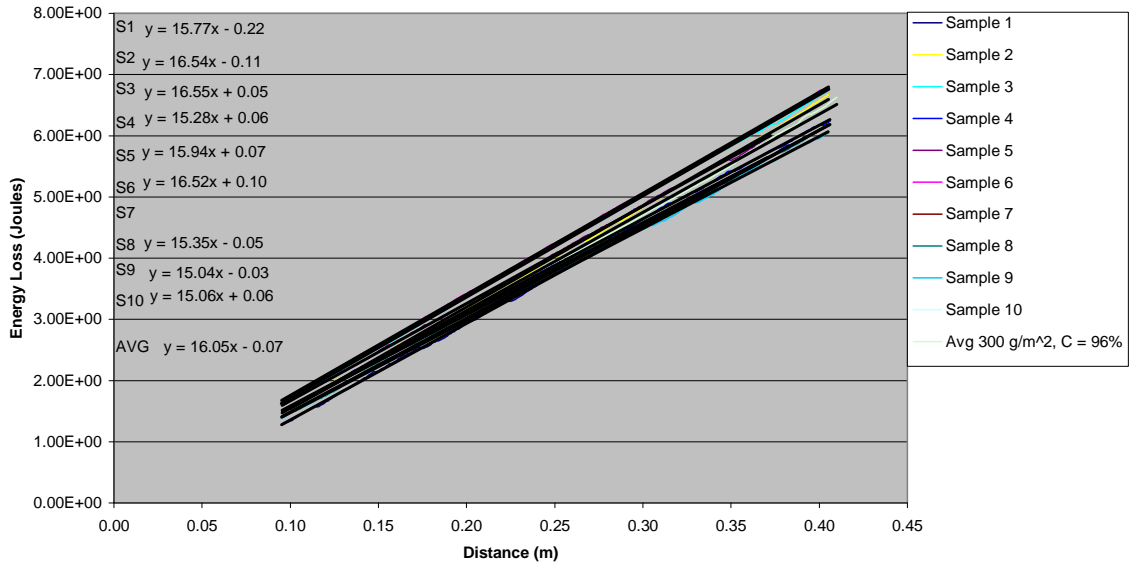
REFINED 560 csf + CATIONIC STARCH (15 Kg/Ton) - 300 g/m²
CONSISTENCY = 68 %
SPLITTING WEIGHT 1100 gr



REFINED 560 csf + CATIONIC STARCH (15 Kg/Ton) - 300 g/m²
CONSISTENCY = 85 %
SPLITTING WEIGHT 1980 gr

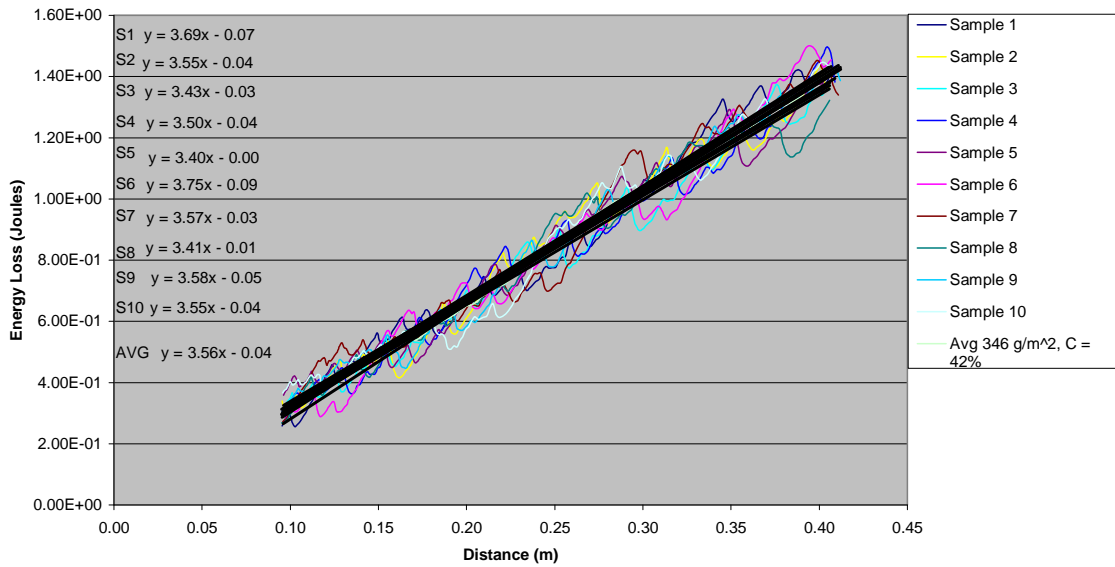


REFINED 560 csf + CATIONIC STARCH (15 Kg/Ton) - 300 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1980 gr

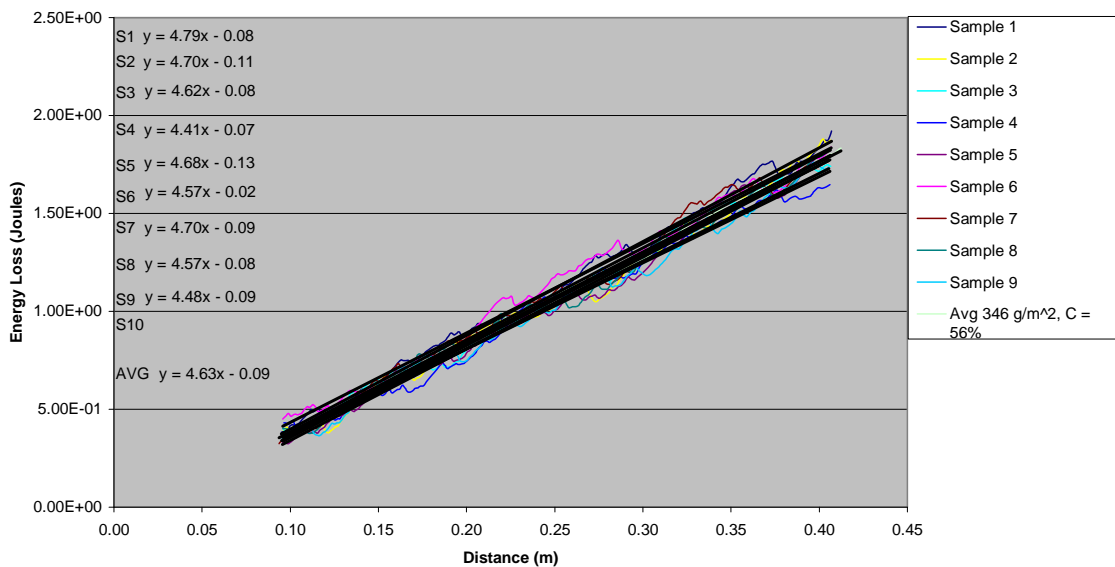


Case 11: Refining 560 C.S.F.; ASH 23% (Normal Clay), 15 kg/ton C-Starch;
Basis Weight [346 g/m²]

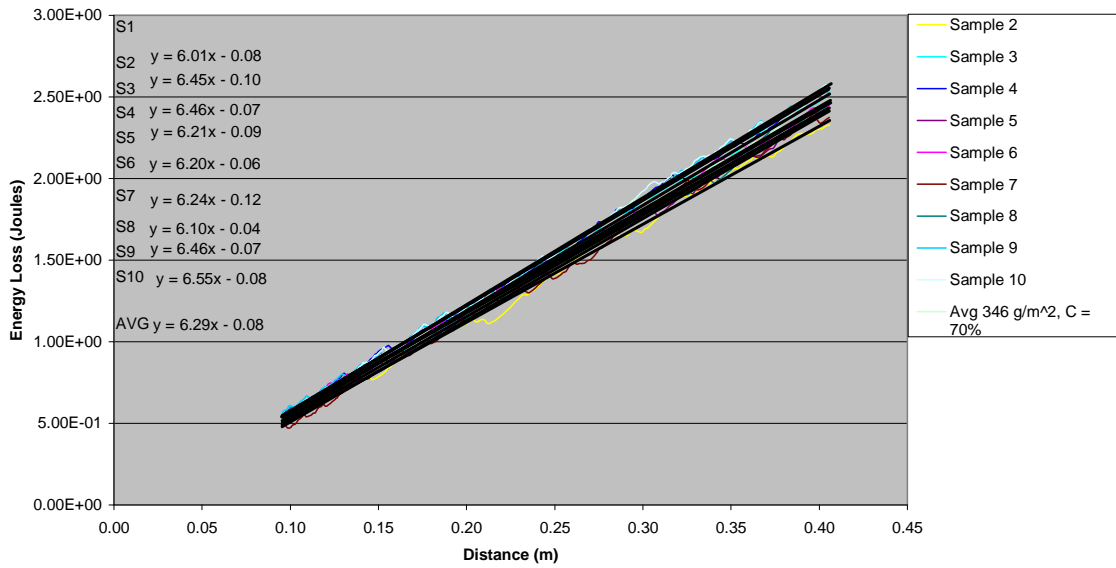
REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 15 Kg/Ton - 346 g/m²
 CONSISTENCY = 42 %
 SPLITTING WEIGHT 1100 gr



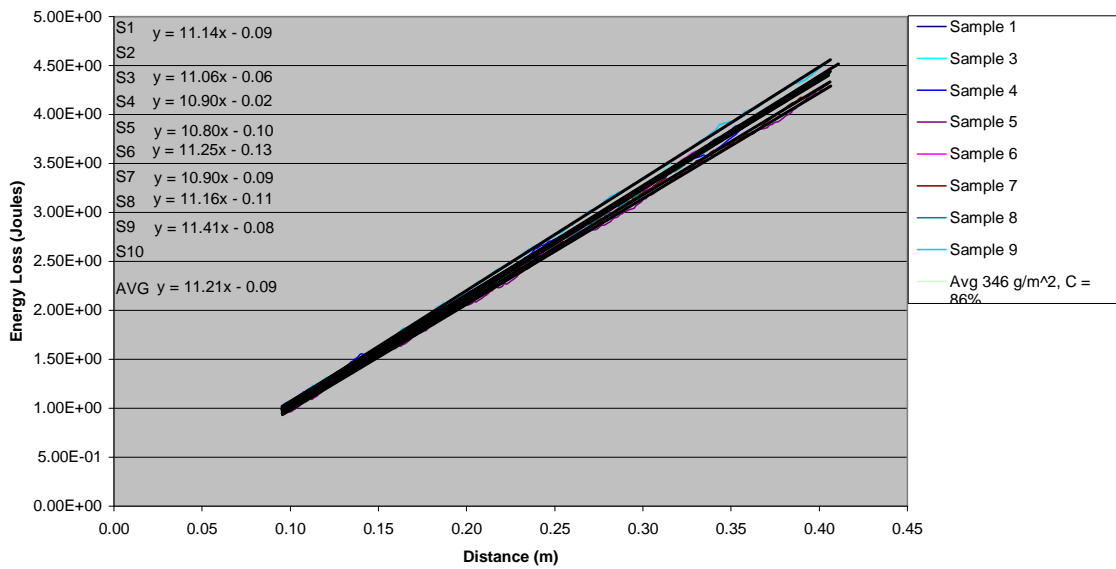
REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 15 Kg/Ton - 346 g/m²
 CONSISTENCY = 56 %
 SPLITTING WEIGHT 1100 gr



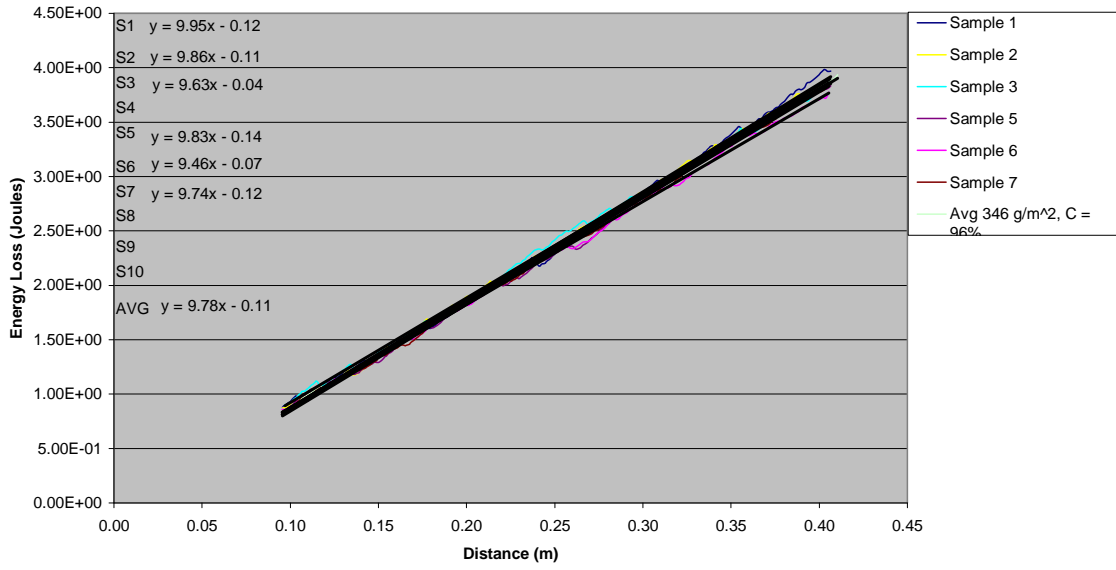
REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 15 Kg/Ton - 346 g/m²
 CONSISTENCY = 70 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 15 Kg/Ton - 346 g/m²
 CONSISTENCY = 86 %
 SPLITTING WEIGHT 1540 gr

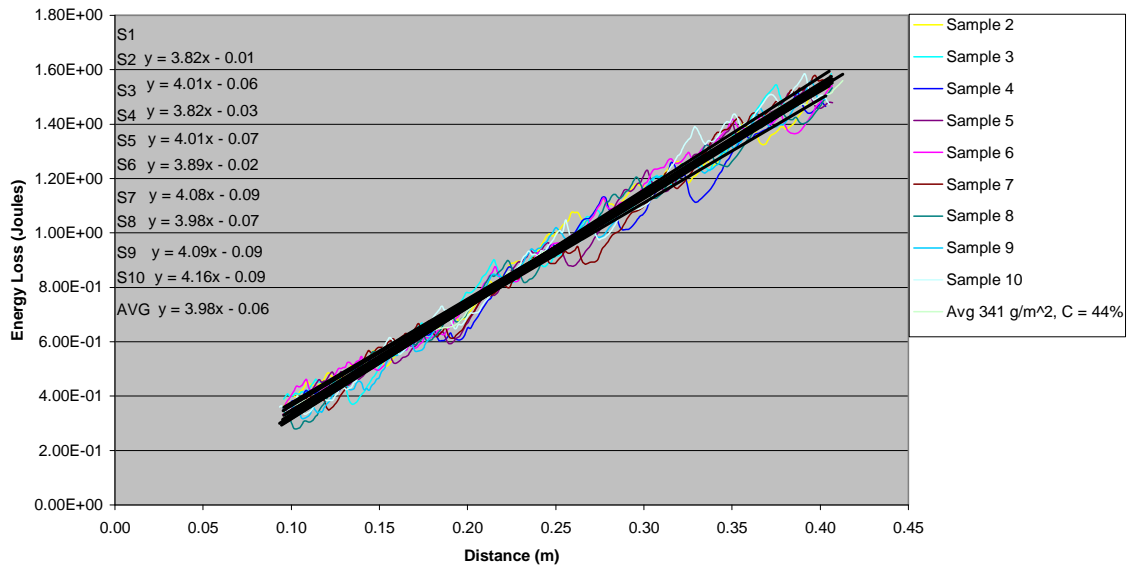


REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 15 Kg/Ton - 346 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1540 gr

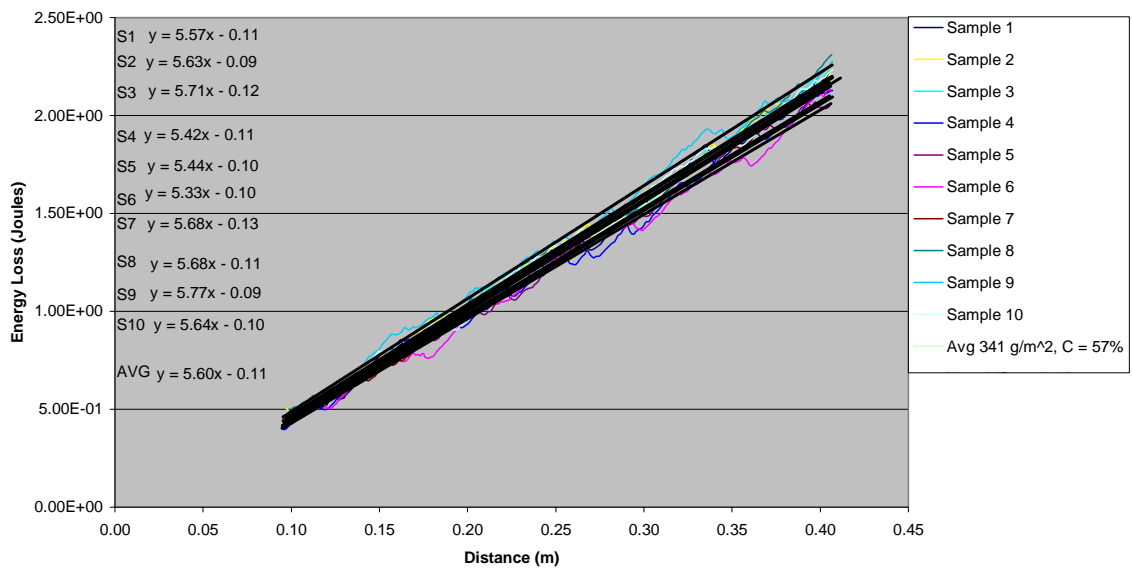


Case 12: Refining 560 C.S.F.; ASH 23% (Normal Clay), 30 kg/ton C-Starch;
Basis Weight [341 g/m²]

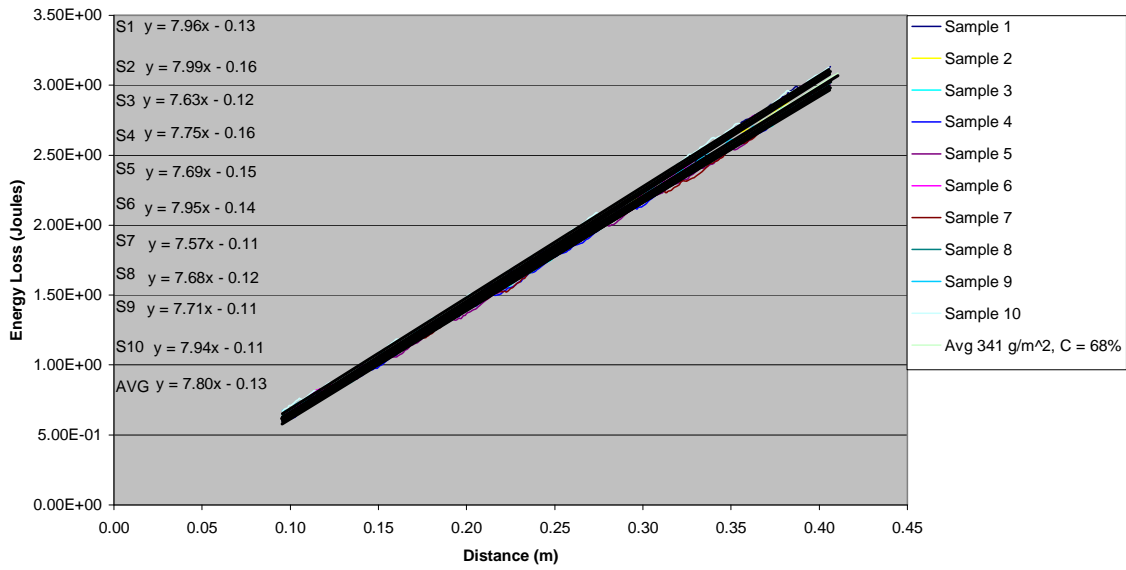
REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 30 Kg/Ton - 341 g/m²
 CONSISTENCY = 44 %
 SPLITTING WEIGHT 1100 gr



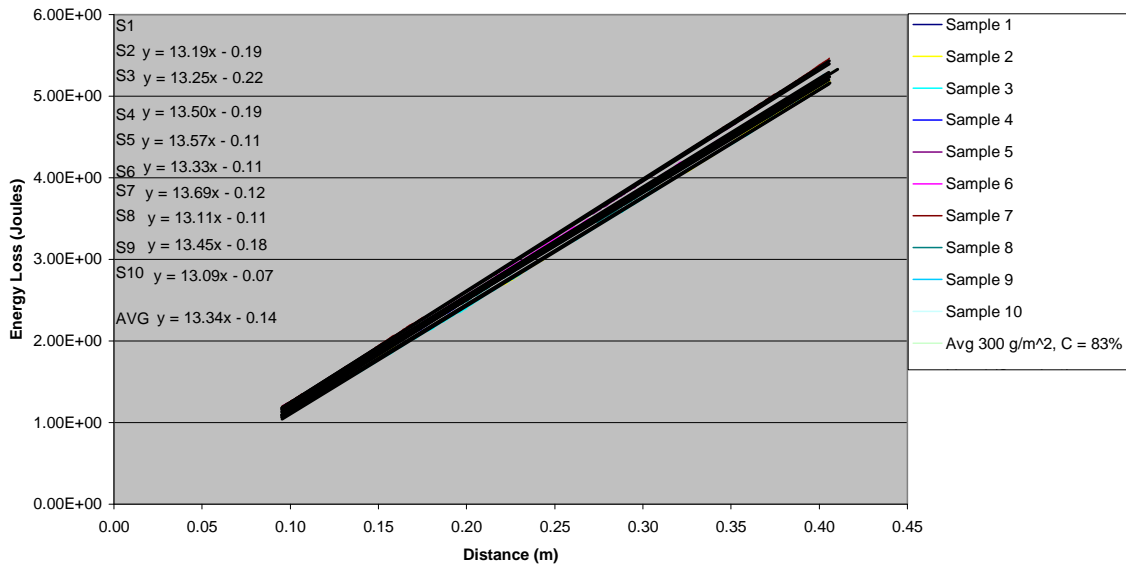
REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 30 Kg/Ton - 341 g/m²
 CONSISTENCY = 57 %
 SPLITTING WEIGHT 1100 gr



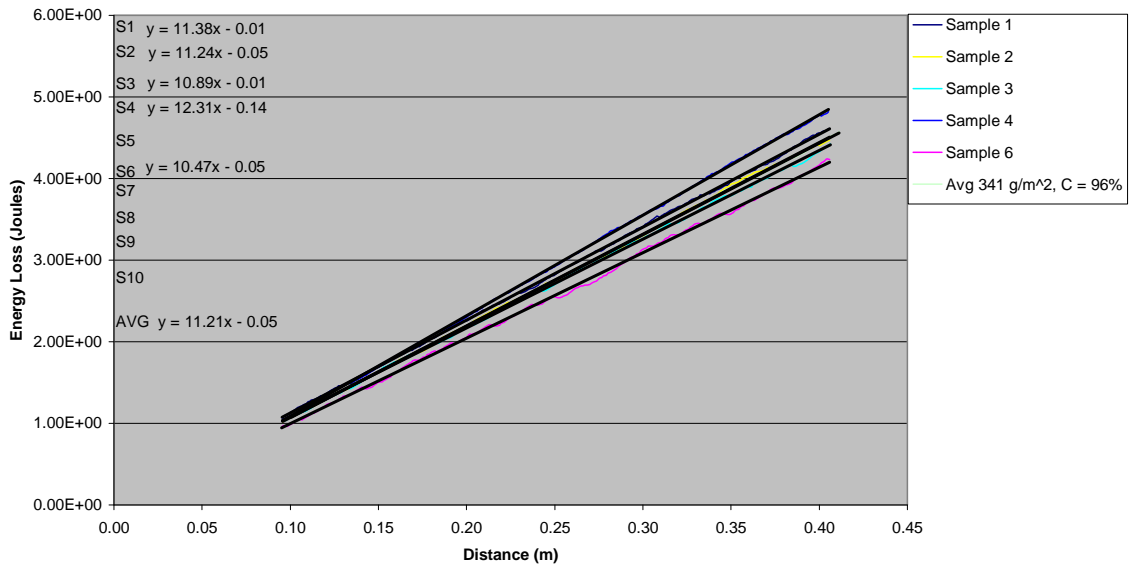
REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 30 Kg/Ton - 341 g/m²
 CONSISTENCY = 68 %
 SPLITTING WEIGHT 1100 gr



REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 30 Kg/Ton - 300 g/m²
 CONSISTENCY = 83 %
 SPLITTING WEIGHT 1540 gr



REFINED 560 csf / Ash = 23% / CATIONIC STARCH = 30 Kg/Ton - 341 g/m²
 CONSISTENCY = 96 %
 SPLITTING WEIGHT 1540 gr



**APPENDIX C: MEAN AND STANDARD DEVIATION FOR APPARATUS
ENERGY LOSS**

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)			
				APPARATUS LOSS	Std Dev	FRICTION	SPLITTING
CASE 1: REF 560 csf; NO CHEMICALS	101	1100	46	3.11	0.09	2.43	0.68
		1100	63	4.55	0.12	2.36	2.19
		1100	78	7.47	0.21	2.36	5.11
		1100	86	9.39	0.16	2.36	7.03
		1100	95	7.75	0.19	2.36	5.39
CASE 1: REF 560 csf; NO CHEMICALS	191	1100	20	2.90	0.09	2.49	0.41
		1100	41	3.19	0.09	2.43	0.76
		1100	56	3.87	0.06	2.36	1.51
		1100	71	6.58	0.10	2.36	4.22
		1100	78	8.58	0.20	2.36	6.22
CASE 1: REF 560 csf; NO CHEMICALS	277	1100	41	3.35	0.08	2.43	0.92
		1100	57	4.12	0.11	2.36	1.76
		1100	72	7.47	0.24	2.36	5.11
		1100	79	10.09	0.19	2.36	7.73
		1100	96	10.39	0.28	2.36	8.03
CASE 1: REF 560 csf; NO CHEMICALS	341	1100	22	3.32	0.12	2.49	0.83
		1100	43	3.52	0.04	2.43	1.09
		1100	57	4.34	0.15	2.36	1.98
		1100	68	6.65	0.17	2.36	4.29
		1540	85	13.49	0.19	2.67	10.82
		1540	96	12.65	0.45	2.67	9.98

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)			
				APPARATUS LOSS	Std Dev	FRICTION	SPLITTING
CASE 2: REF 740 csf; NO CHEMICALS	99	250	22	1.42	0.02	1.42	0.00
		250	46	1.54	0.02	1.36	0.23
		250	60	1.68	0.06	1.31	0.37
		1100	68	3.29	0.19	2.36	0.93
		466	72	3.30	0.13	1.82	1.48
CASE 2: REF 740 csf; NO CHEMICALS	199	1100	95	5.30	0.14	2.36	2.94
		250	18	1.47	0.03	1.42	0.05
		466	21	2.02	0.10	2.02	0.00
		1100	29	2.49	0.12	2.49	0.00
		660	40	2.22	0.07	2.15	0.07
CASE 2: REF 740 csf; NO CHEMICALS	302	660	59	2.49	0.09	2.05	0.44
		1100	72	4.24	0.12	2.36	1.88
		1100	76	5.15	0.15	2.36	2.79
		1100	95	5.80	0.14	2.36	3.44
		250	18	1.52	0.00	1.42	0.10
CASE 2: REF 740 csf; NO CHEMICALS	396	1100	24	2.56	0.08	2.49	0.07
		1100	33	2.63	0.05	2.49	0.14
		1100	42	2.68	0.16	2.43	0.25
		1100	53	2.77	0.07	2.36	0.41
		1100	67	3.84	0.08	2.36	1.48
CASE 2: REF 740 csf; NO CHEMICALS	396	1100	85	7.48	0.23	2.36	5.12
		1100	92	6.86	0.11	2.36	4.50
		250	18	1.45	0.04	1.42	0.03
		466	22	2.29	0.07	1.42	0.87
		660	35	2.51	0.05	1.42	1.09
CASE 2: REF 740 csf; NO CHEMICALS	396	1100	42	2.86	0.06	2.43	0.43
		1100	48	3.05	0.08	2.43	0.62
		1100	68	4.46	0.24	2.36	2.10
		1100	83	8.53	0.23	2.36	6.17
		1100	95	7.01	0.17	2.36	4.65

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)			
				APPARATUS LOSS	Std Dev	FRICTION	SPLITTING
CASE 3: REF 560 csf; 17% ASH (NC) NO STARCH	113	1100	30	2.66	0.11	2.49	0.17
		1100	45	3.02	0.11	2.43	0.59
		1100	57	3.41	0.14	2.36	1.05
		1100	72	4.76	0.18	2.36	2.40
		1100	79	5.75	0.21	2.36	3.39
		1100	95	5.18	0.12	2.36	2.82
CASE 3: REF 560 csf; 17% ASH (NC) NO STARCH	202	1100	29	2.91	0.12	2.49	0.42
		1100	43	3.15	0.17	2.43	0.72
		1100	58	3.65	0.15	2.36	1.29
		1100	76	5.69	0.16	2.36	3.33
		1100	86	7.38	0.13	2.36	5.02
		1100	95	5.54	0.15	2.36	3.18
CASE 3: REF 560 csf; 17% ASH (NC) NO STARCH	311	1100	28	3.15	0.08	2.49	0.66
		1100	39	3.26	0.10	2.43	0.83
		1100	55	3.71	0.11	2.36	1.35
		1100	69	4.94	0.11	2.36	2.58
		1100	89	8.56	0.21	2.36	6.20
		1100	93	8.31	0.11	2.36	5.95
CASE 3: REF 560 csf; 17% ASH (NC) NO STARCH	400	1100	30	3.27	0.08	2.49	0.78
		1100	36	3.32	0.13	2.43	0.89
		1100	54	3.95	0.16	2.36	1.59
		1100	67	5.00	0.18	2.36	2.64
		1100	83	8.48	0.27	2.36	6.12
		1100	92	8.74	0.21	2.36	6.38

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)			
				APPARATUS LOSS	Std Dev	FRICTION	SPLITTING
CASE 4: REF 440 csf; NO CHEMICALS	300	1100	36	3.41	0.11	2.49	0.92
		1100	54	4.43	0.10	2.36	2.07
		1100	70	6.85	0.16	2.36	4.49
		1100	78	9.65	0.29	2.36	7.29
		1540	95	11.90	0.16	2.67	9.23
CASE 5: REF 560 csf; 13% ASH (NC) NO STARCH	314	1100	39	3.32	0.12	2.43	0.89
		1100	58	4.06	0.10	2.36	1.70
		1100	71	5.57	0.16	2.36	3.21
		1100	82	7.77	0.17	2.36	5.41
		1100	96	7.79	0.46	2.36	5.43
CASE 6: REF 560 csf; 22% ASH (NC) NO STARCH	305	1100	43	3.24	0.13	2.43	0.81
		1100	56	3.54	0.12	2.36	1.18
		1100	70	4.66	0.12	2.36	2.30
		1100	85	7.00	0.22	2.36	4.64
		1100	95	6.54	0.19	2.36	4.18

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)			
				APPARATUS LOSS	Std Dev	FRICTION	SPLITTING
CASE 7: REF 560 csf; 13% ASH (MC) NO STARCH	317	1100	40	3.30	0.14	2.43	0.87
		1100	59	4.42	0.12	2.36	2.06
		1100	71	6.38	0.13	2.36	4.02
		1100	85	10.58	0.21	2.36	8.22
		1100	96	9.21	0.28	2.36	6.85
CASE 8: REF 560 csf; 18% ASH (MC) NO STARCH	318	1100	40	3.39	0.09	2.43	0.96
		1100	56	4.08	0.13	2.36	1.72
		1100	68	5.37	0.09	2.36	3.01
		1100	86	10.18	0.16	2.36	7.82
		1100	95	9.49	0.45	2.36	7.13
CASE 9: REF 560 csf; 24% ASH (MC) NO STARCH	318	1100	38	3.36	0.09	2.43	0.93
		1100	56	3.96	0.13	2.36	1.60
		1100	73	5.77	0.18	2.36	3.41
		1100	84	8.33	0.17	2.36	5.97
		1100	96	7.22	0.26	2.36	4.86

CASE DESCRIPTION	BASIS WEIGHT (g/m ²)	SPLITTING WEIGHT (g)	SOLIDS %	ENERGY (J/m)		FRICTION	SPLITTING
				APPARATUS LOSS	Std Dev		
CASE 10: REF 560 csf; 15 Kg/Ton C-STARCH NO CLAY	303	1100	39	3.91	0.15	2.43	1.48
		1100	53	5.53	0.13	2.36	3.17
		1100	68	8.87	0.24	2.36	6.51
		1980	85	18.97	0.38	2.97	16.00
		1980	96	15.78	0.67	2.97	12.81
CASE 11: REF 560 csf; 15 Kg/Ton C-STARCH 23% ASH (NC)	346	1100	42	3.54	0.12	2.43	1.11
		1100	56	4.61	0.12	2.36	2.25
		1100	70	6.30	0.19	2.36	3.94
		1540	86	11.20	0.34	2.36	8.84
		1540	96	9.75	0.18	2.67	7.08
CASE 12: REF 560 csf; 30 Kg/Ton C-STARCH 23% ASH (NC)	341	1100	44	3.98	0.12	2.43	1.55
		1100	57	5.59	0.14	2.36	3.23
		1100	68	7.79	0.16	2.36	5.43
		1540	83	13.35	0.21	2.67	10.68
		1540	96	11.26	0.69	2.67	8.59

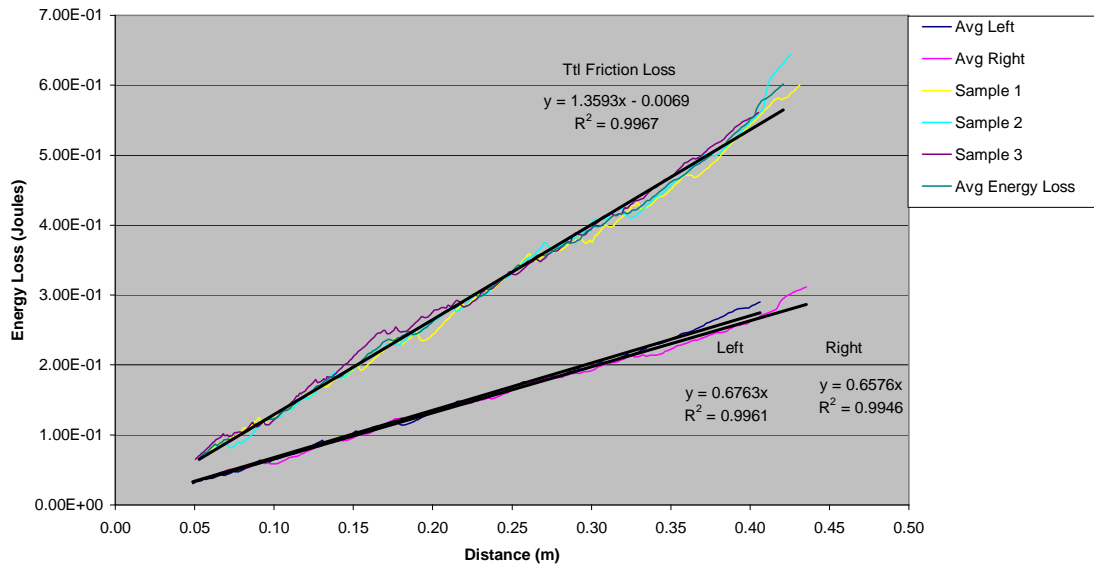
**APPENDIX D: FRICTION ENERGY LOSS VS SPLITTING WEIGHT AND
COUNTER WEIGHT**

Splitting Weight = 125g

ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

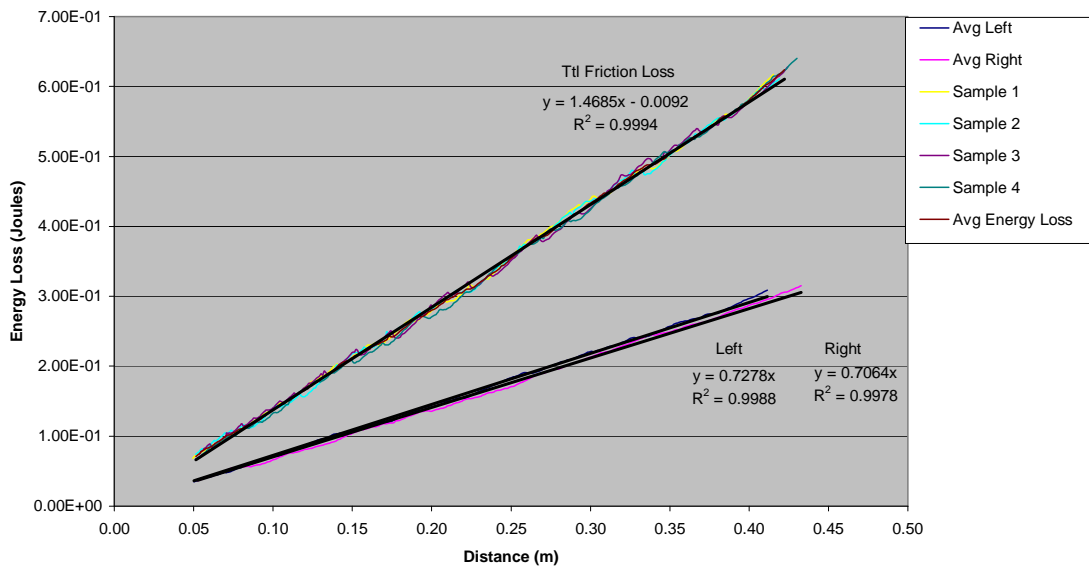
Counter Weight = 4



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

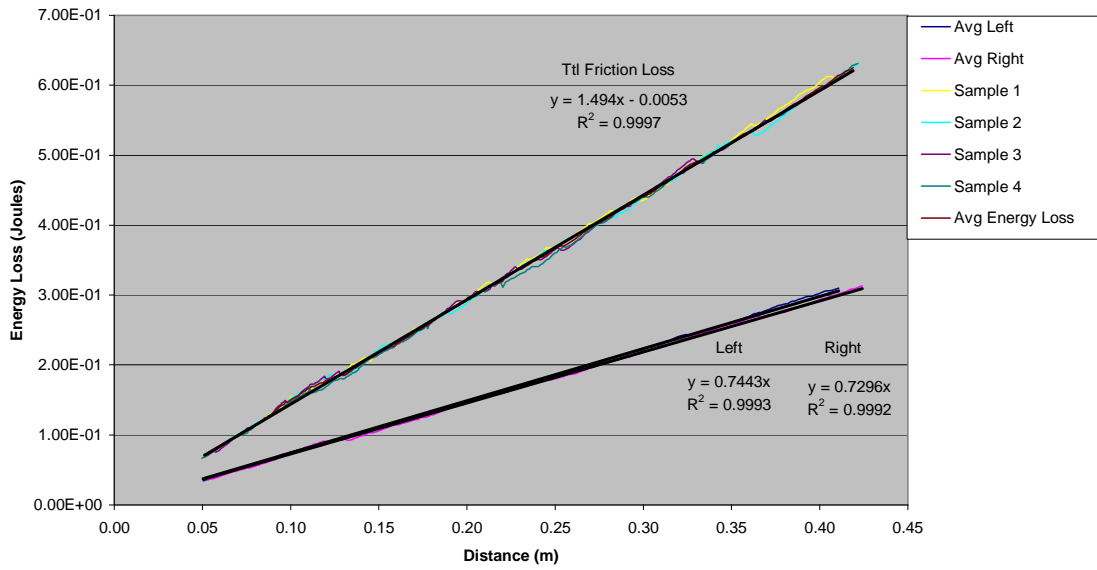
Counter Weight = 10



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

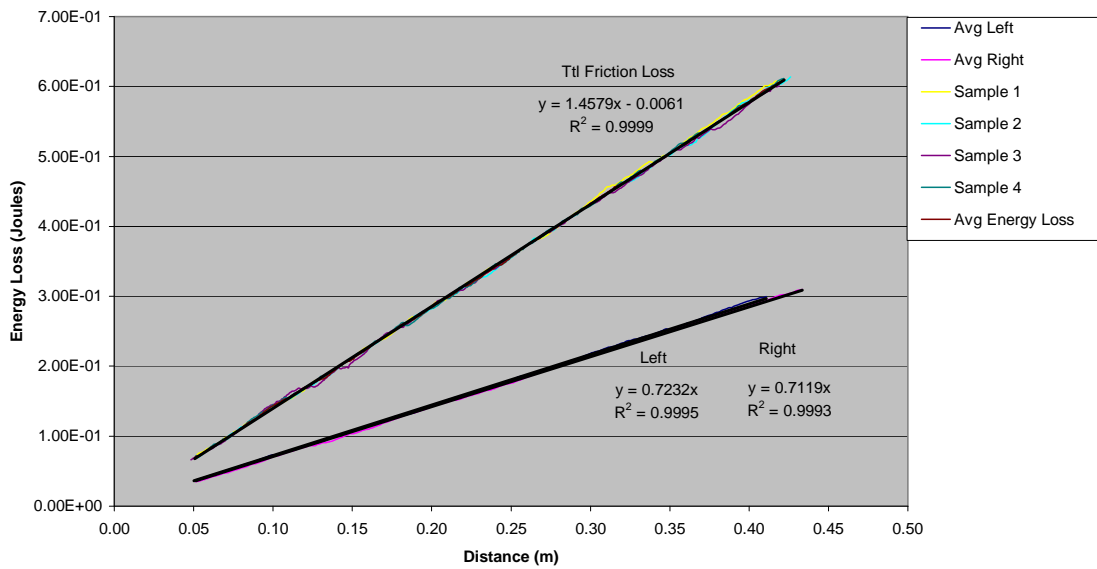
Counter Weight = 20



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

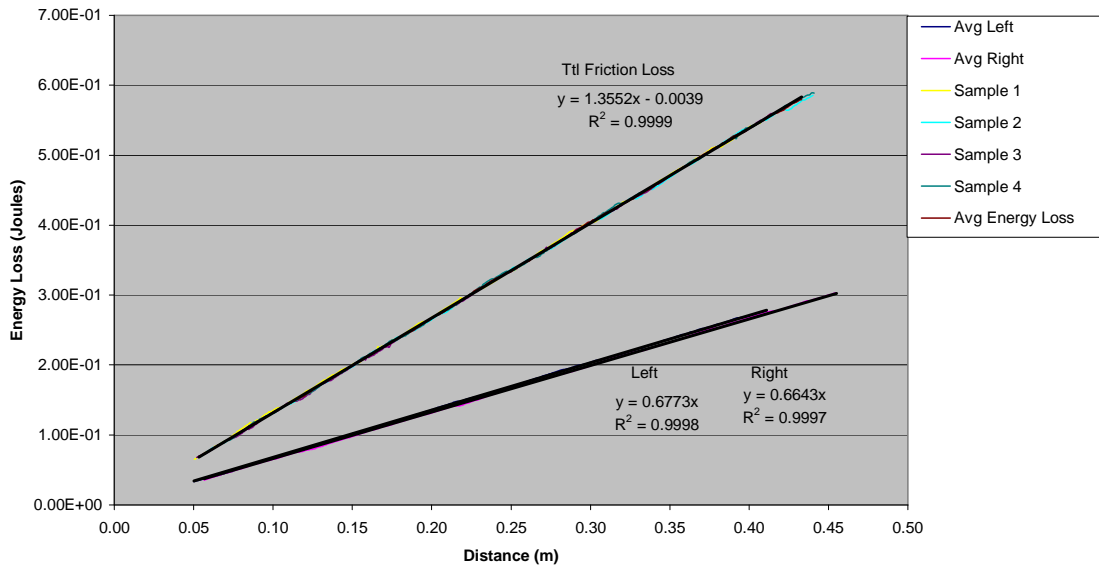
Counter Weight = 30



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

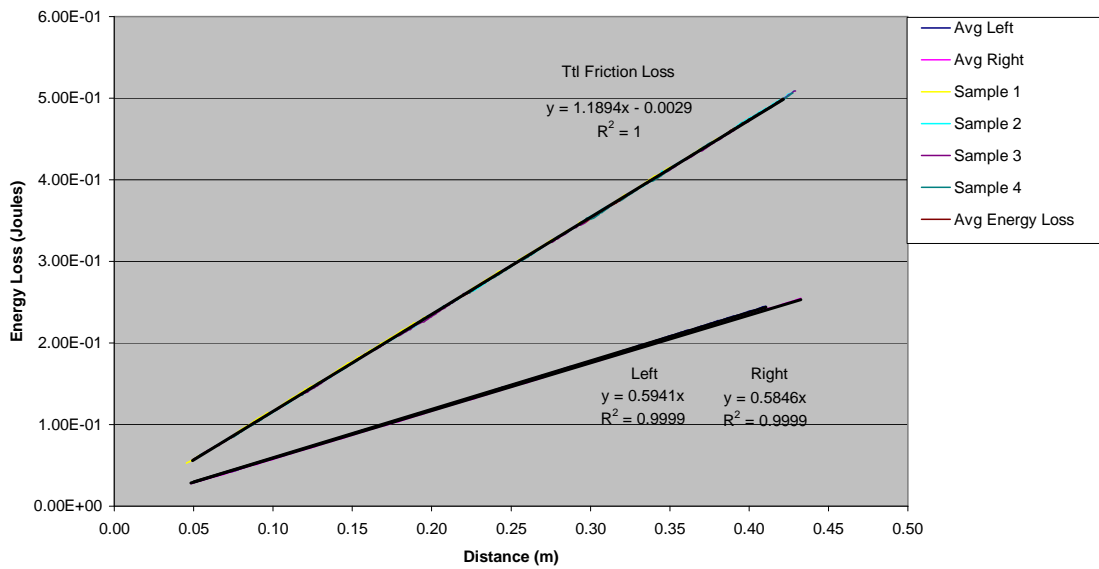
Counter Weight = 40



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

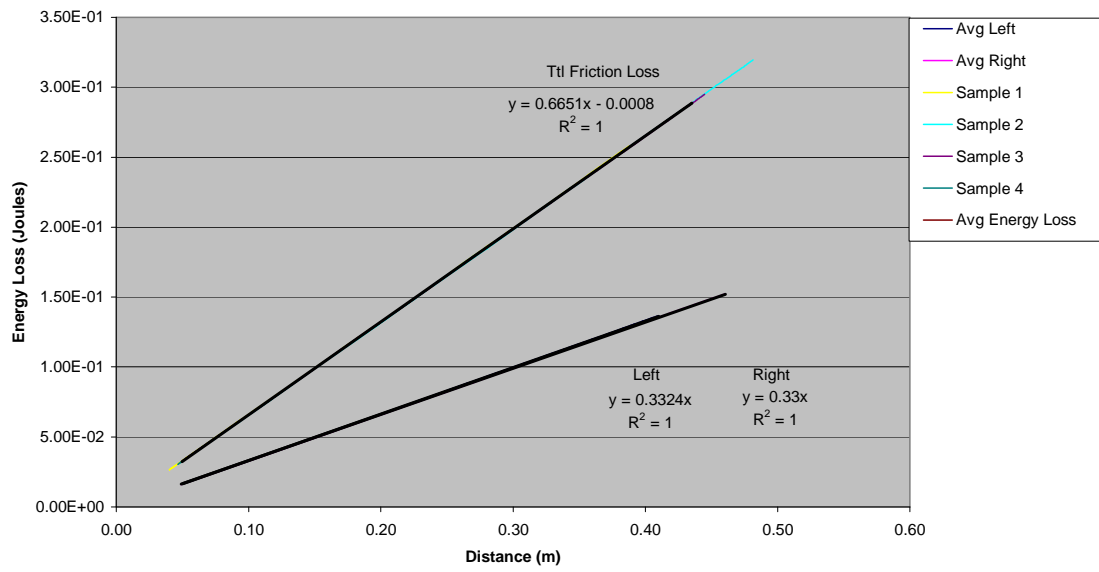
Counter Weight = 55



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 125

Counter Weight = 90



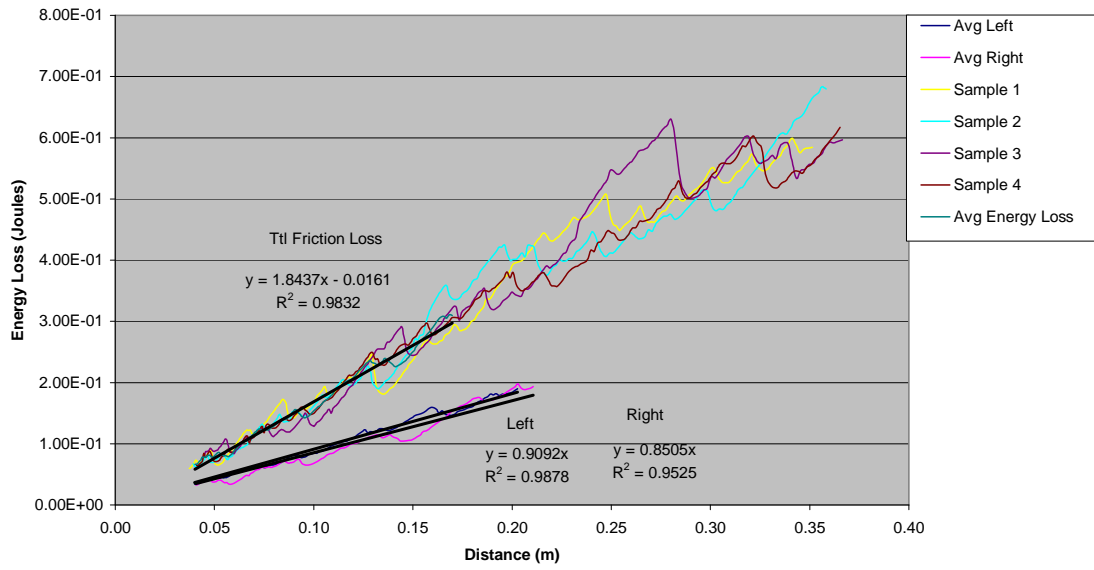
**APPENDIX D: FRICTION ENERGY LOSS VS SPLITTING WEIGHT AND
COUNTER WEIGHT**

Splitting Weight = 233g

ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233

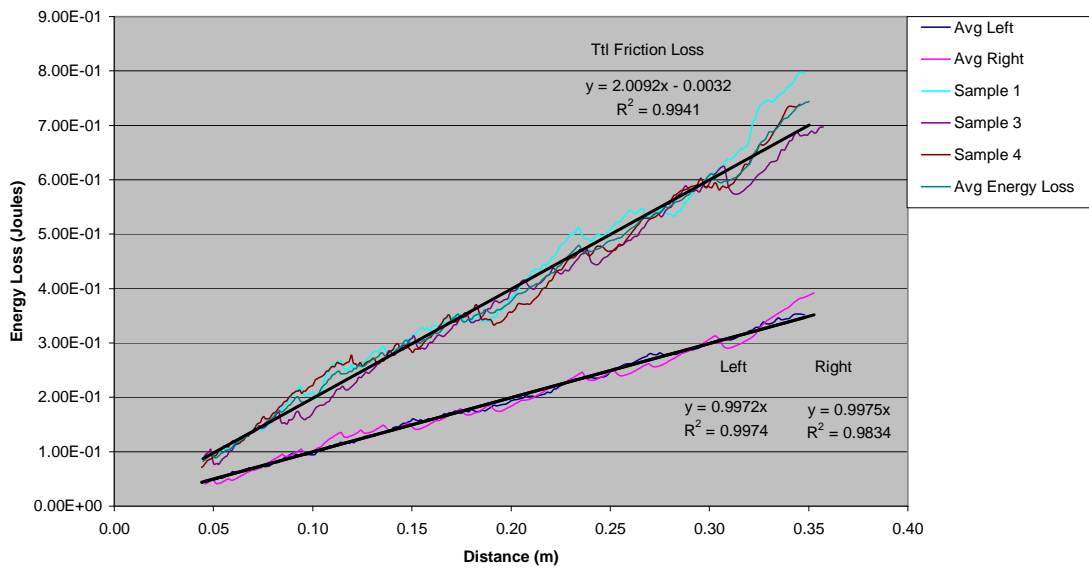
Counter Weight = 4



ENERGY LOSS DUE TO FRICTION

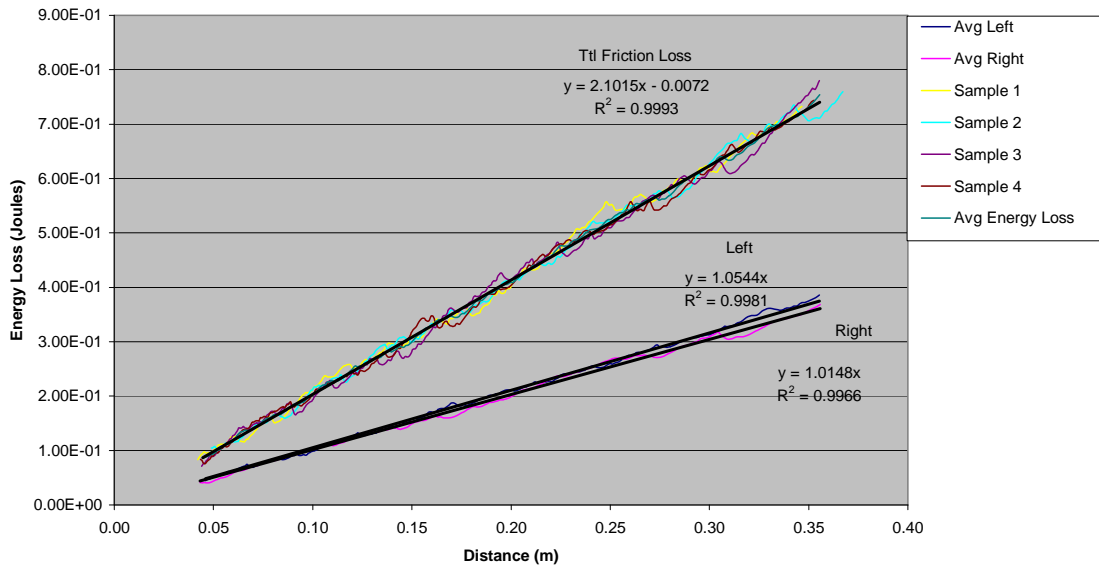
Splitting Weight = 233

Counter Weight = 10



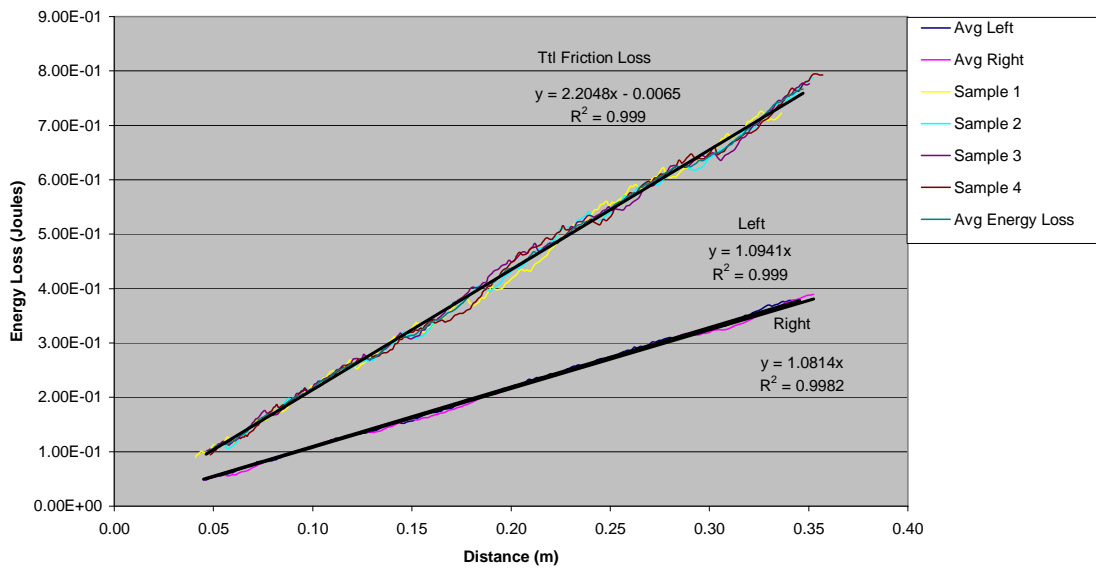
ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233
Counter Weight = 20



ENERGY LOSS DUE TO FRICTION

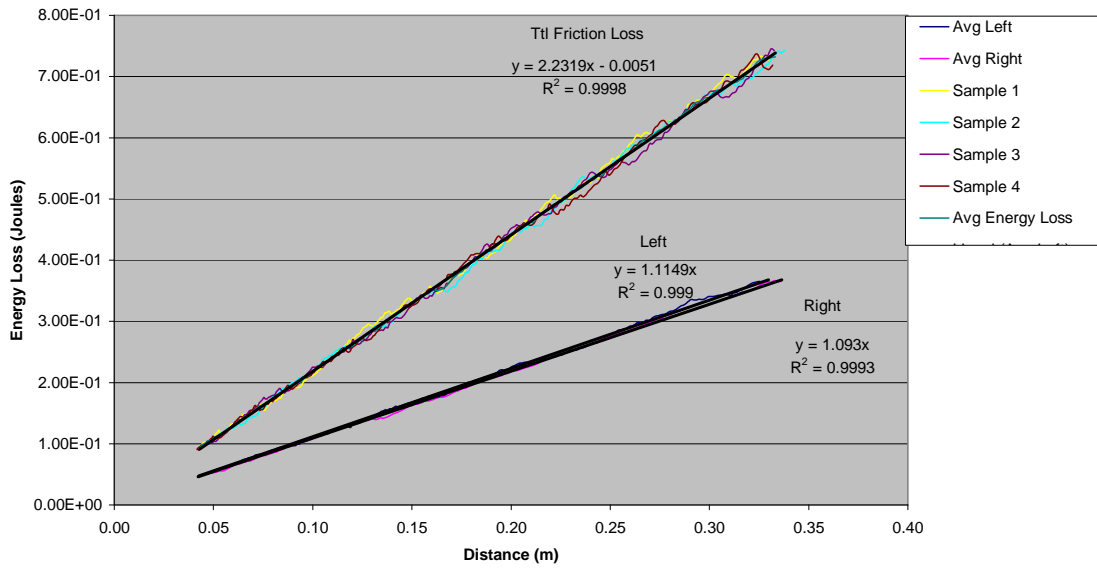
Splitting Weight = 233
Counter Weight = 30



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233

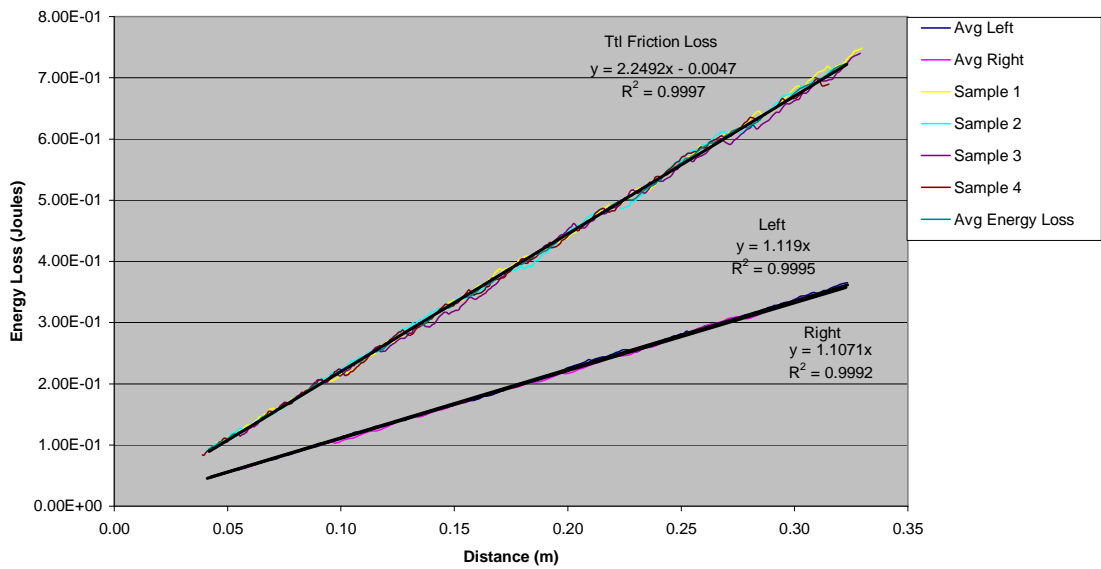
Counter Weight = 40



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233

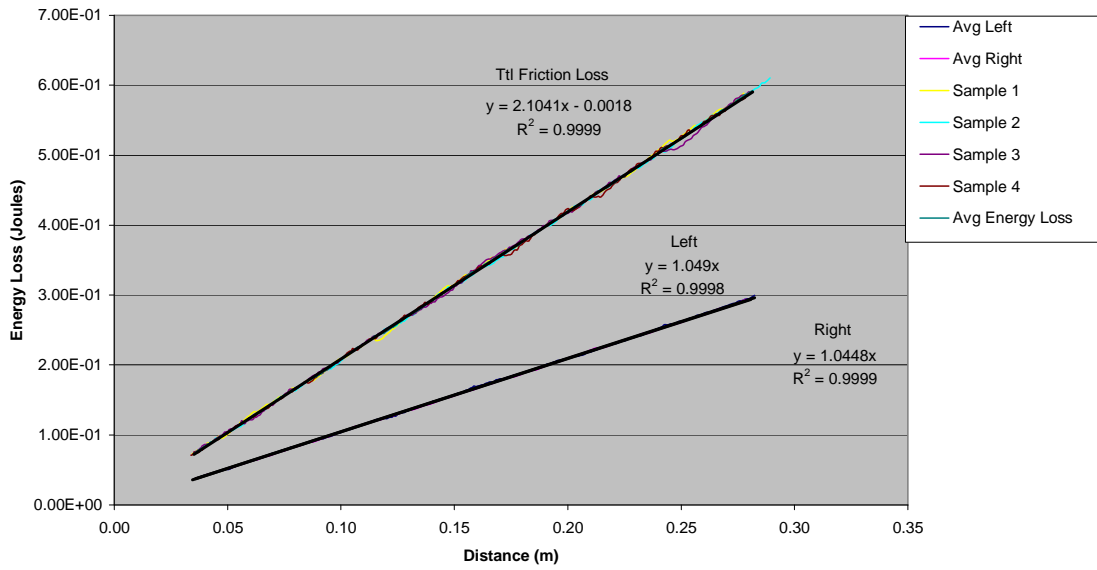
Counter Weight = 55



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233

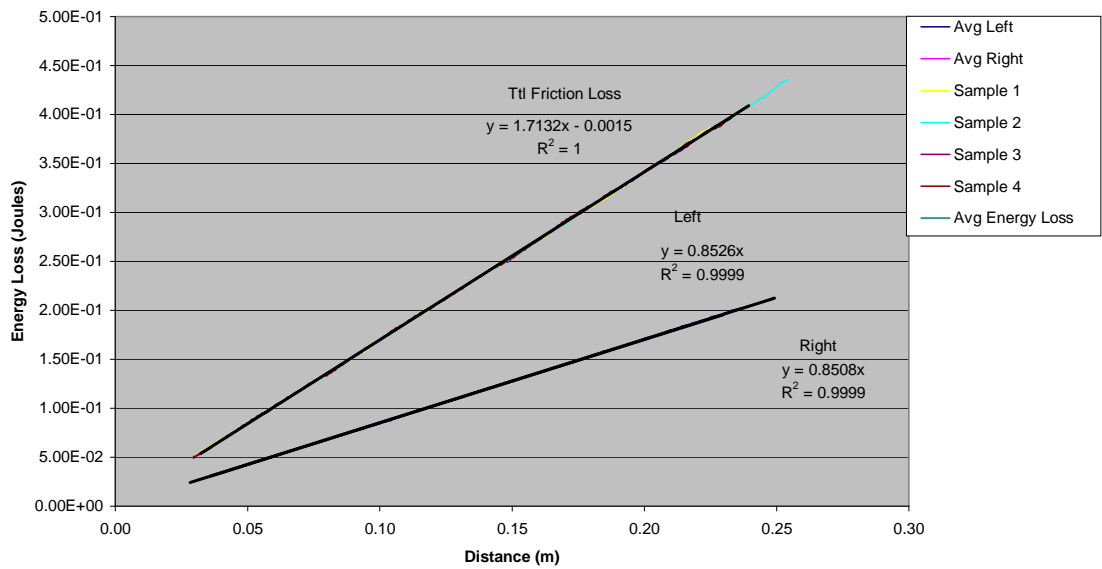
Counter Weight = 90



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233

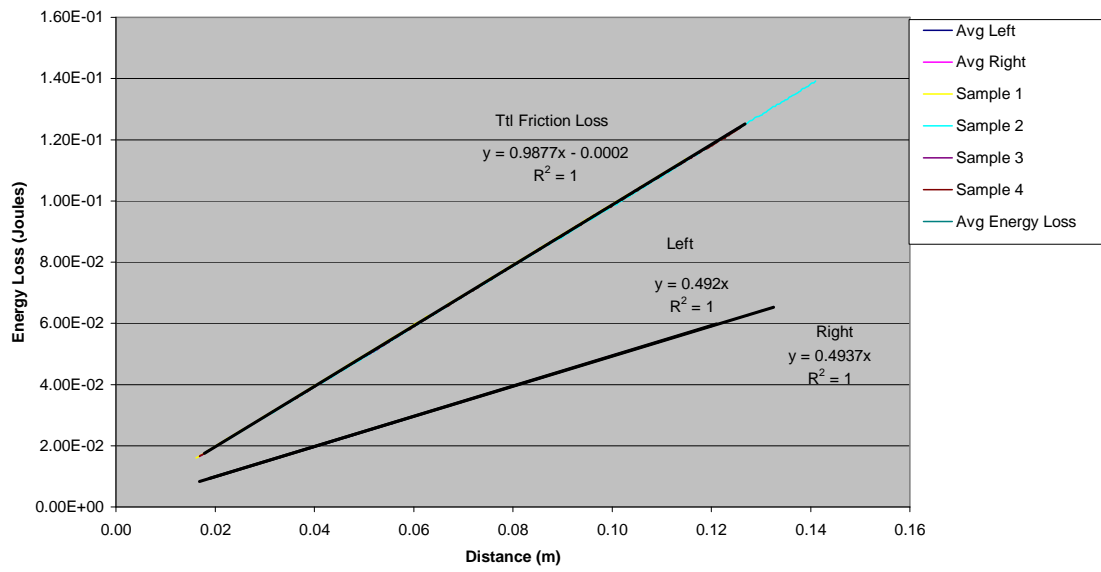
Counter Weight = 130



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 233

Counter Weight = 180



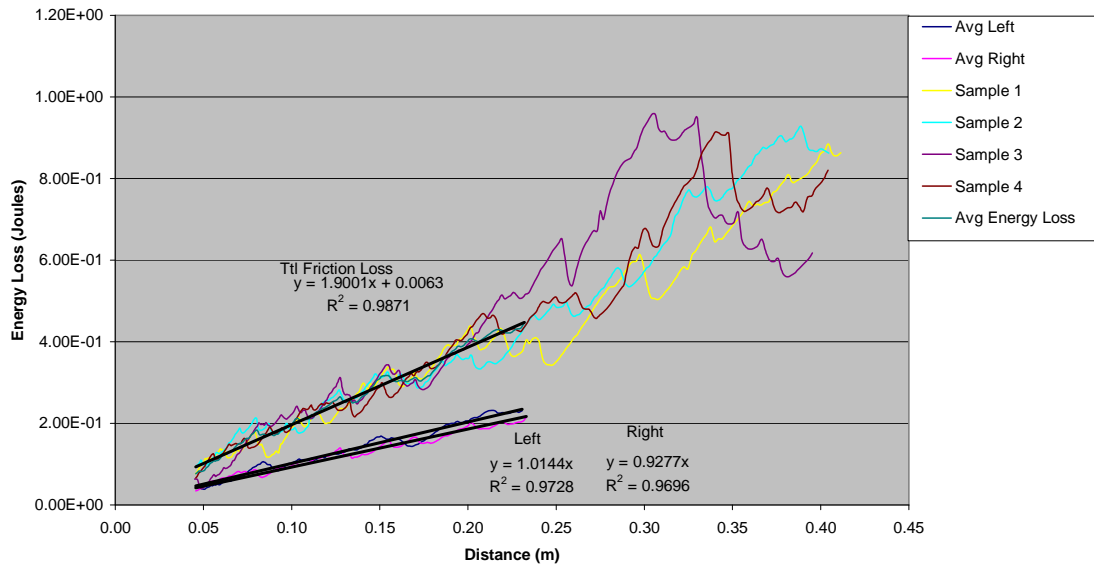
**APPENDIX D: FRICTION ENERGY LOSS VS SPLITTING WEIGHT AND
COUNTER WEIGHT**

Splitting Weight = 330g

ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

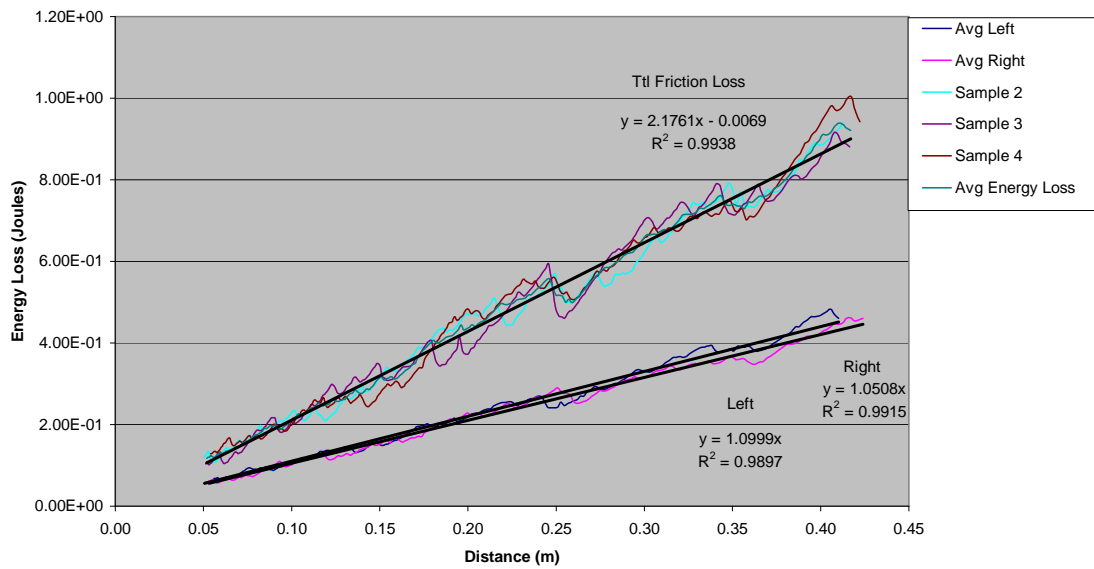
Counter Weight = 4



ENERGY LOSS DUE TO FRICTION

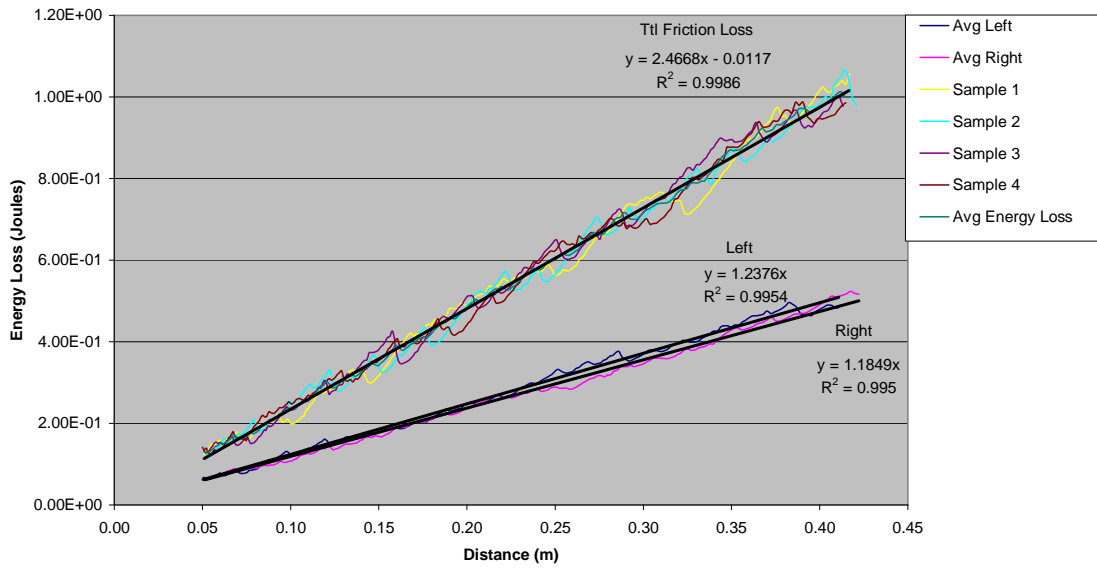
Splitting Weight = 330

Counter Weight = 10



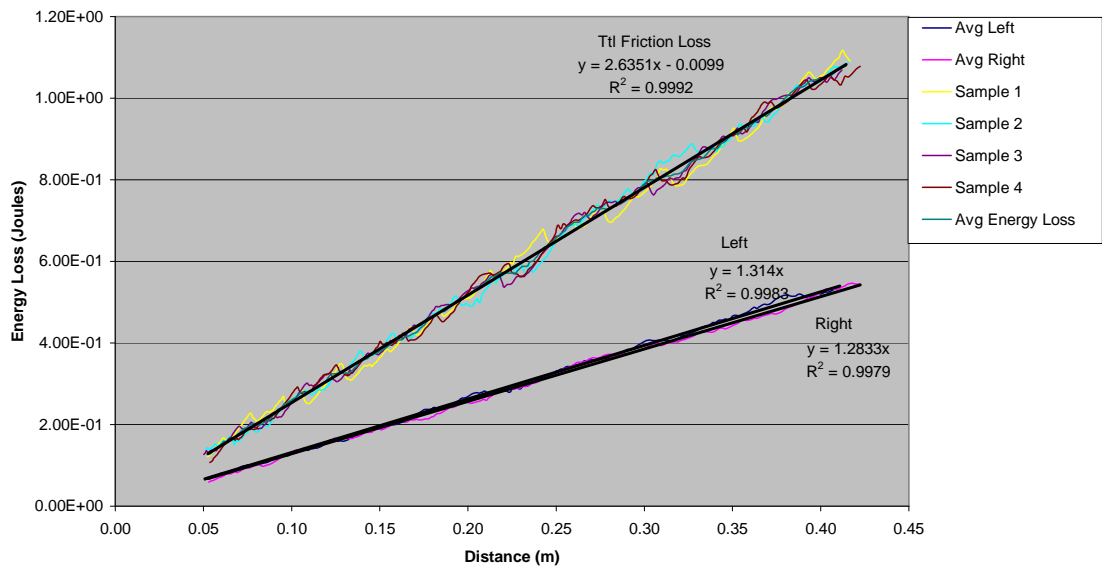
ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330
Counter Weight = 20



ENERGY LOSS DUE TO FRICTION

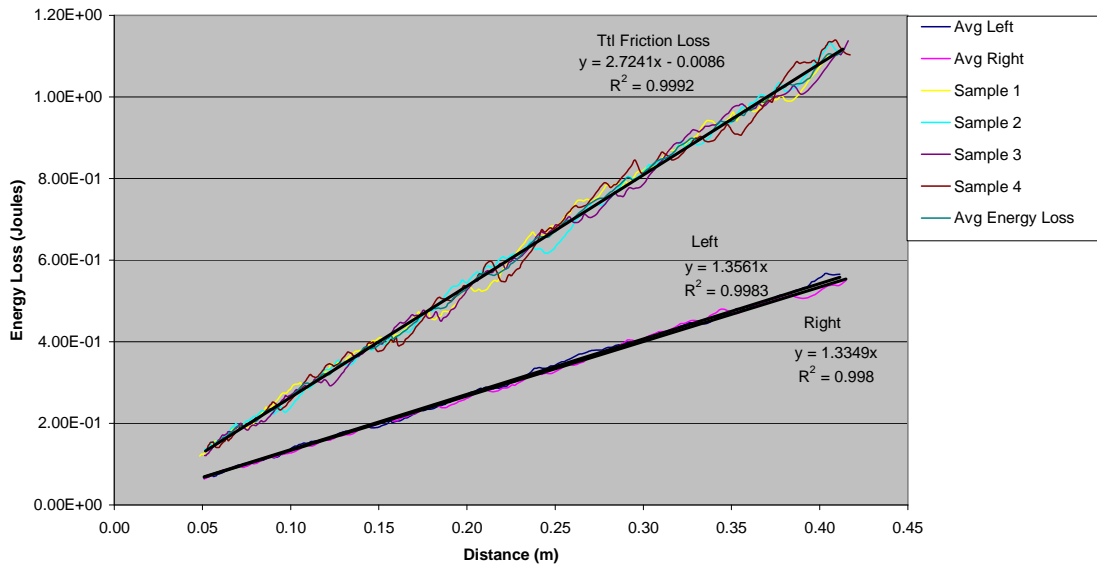
Splitting Weight = 330
Counter Weight = 30



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

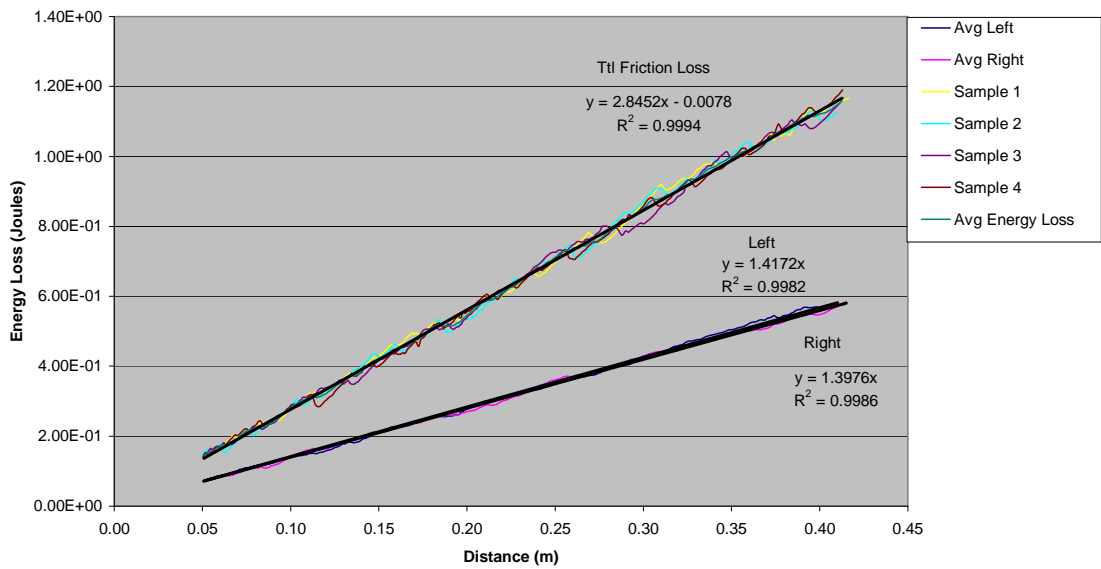
Counter Weight = 40



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

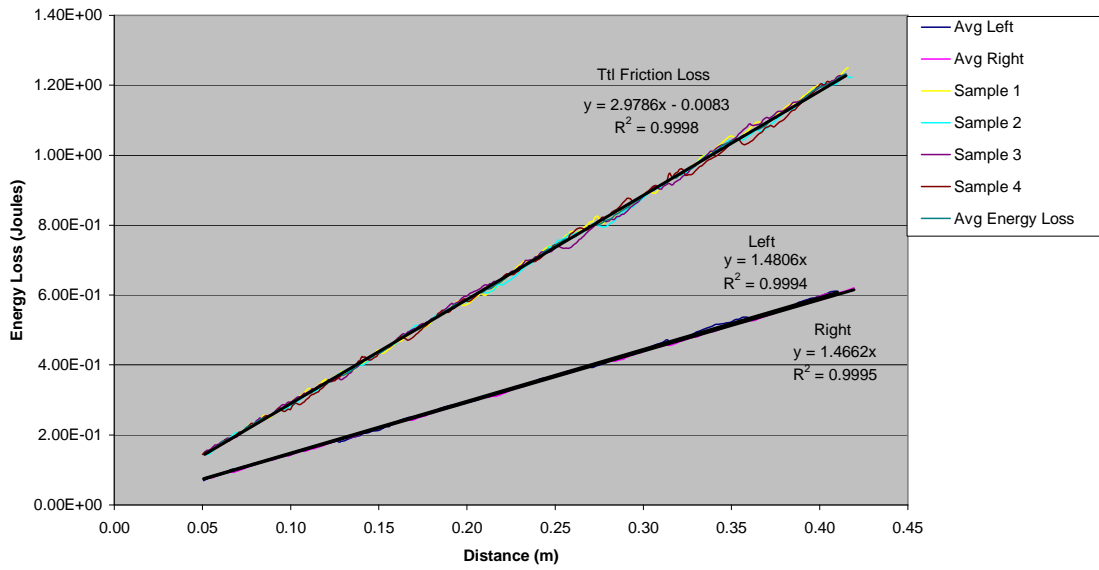
Counter Weight = 55



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

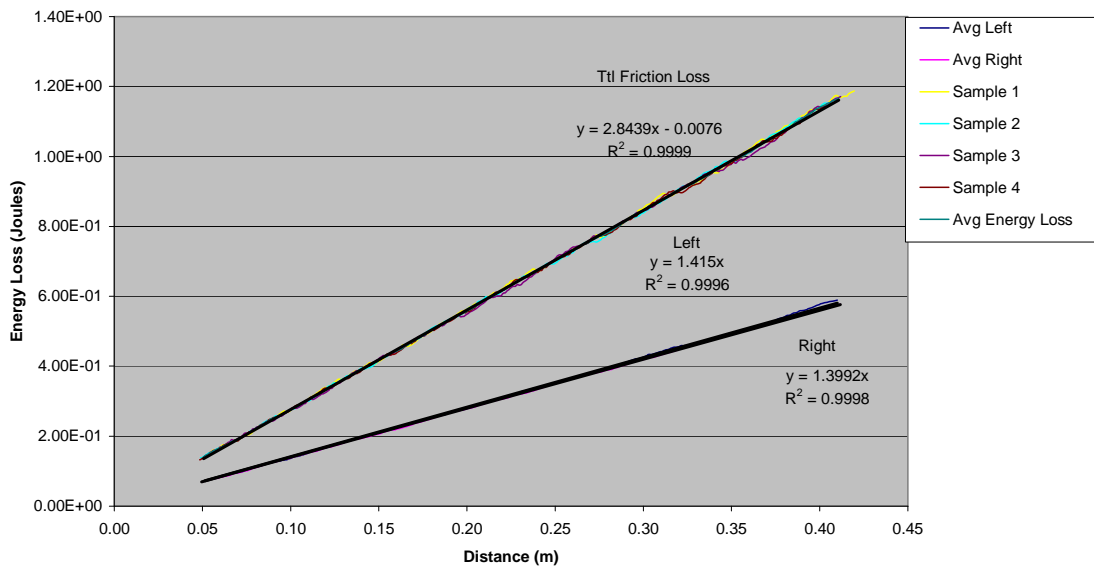
Counter Weight = 90



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

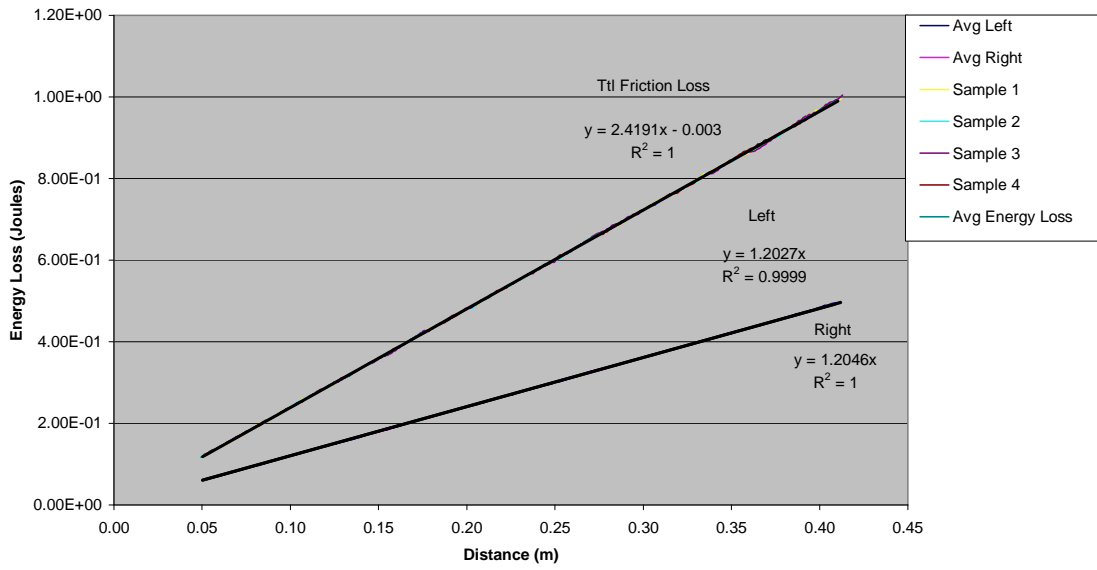
Counter Weight = 130



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

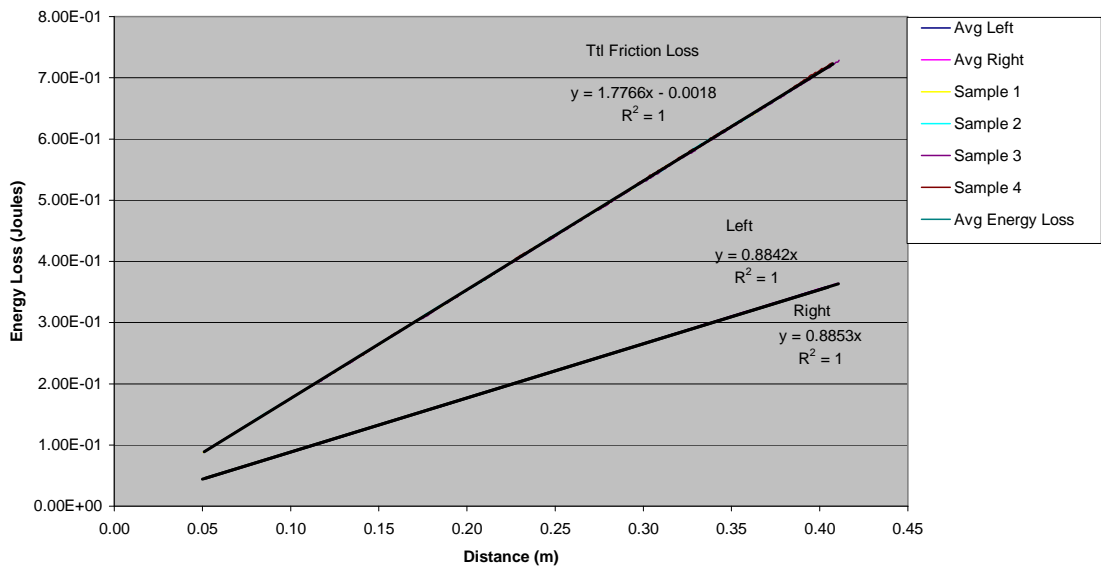
Counter Weight = 180



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

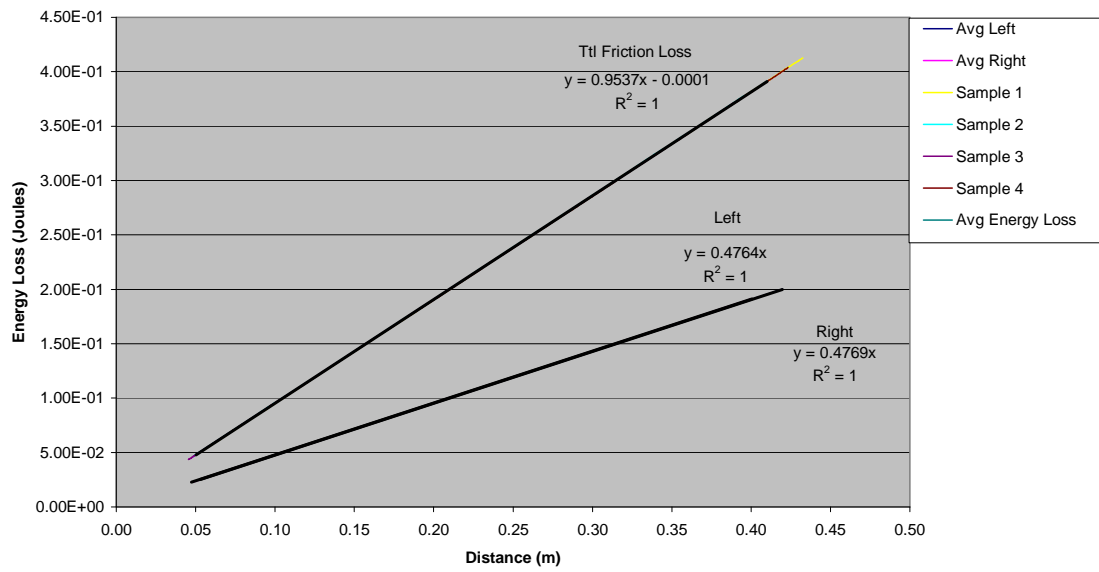
Counter Weight = 230



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 330

Counter Weight = 280

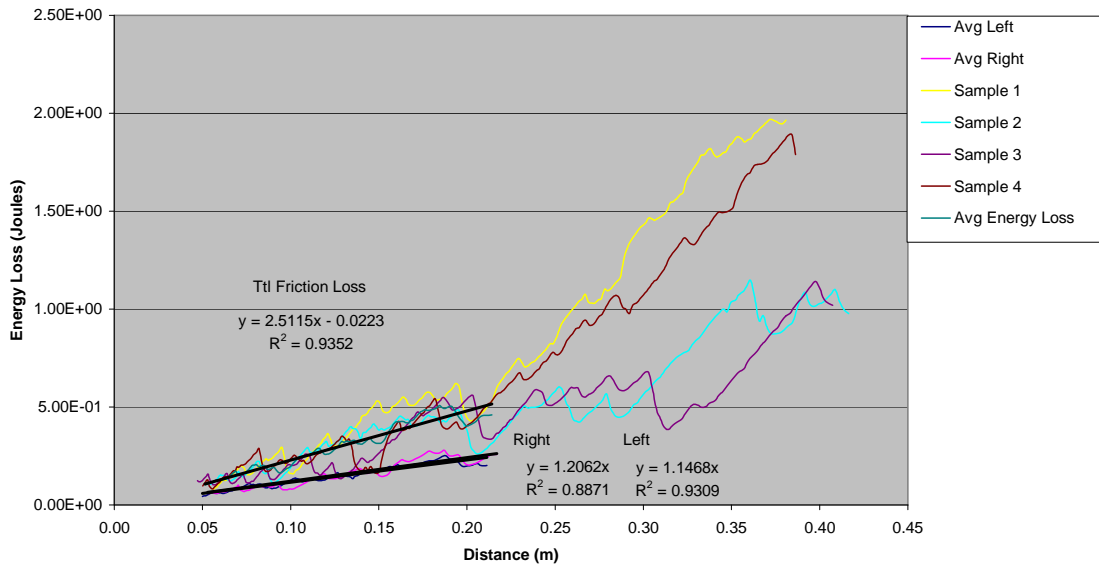


**APPENDIX D: FRICTION ENERGY LOSS VS SPLITTING WEIGHT AND
COUNTER WEIGHT**

Splitting Weight = 550g

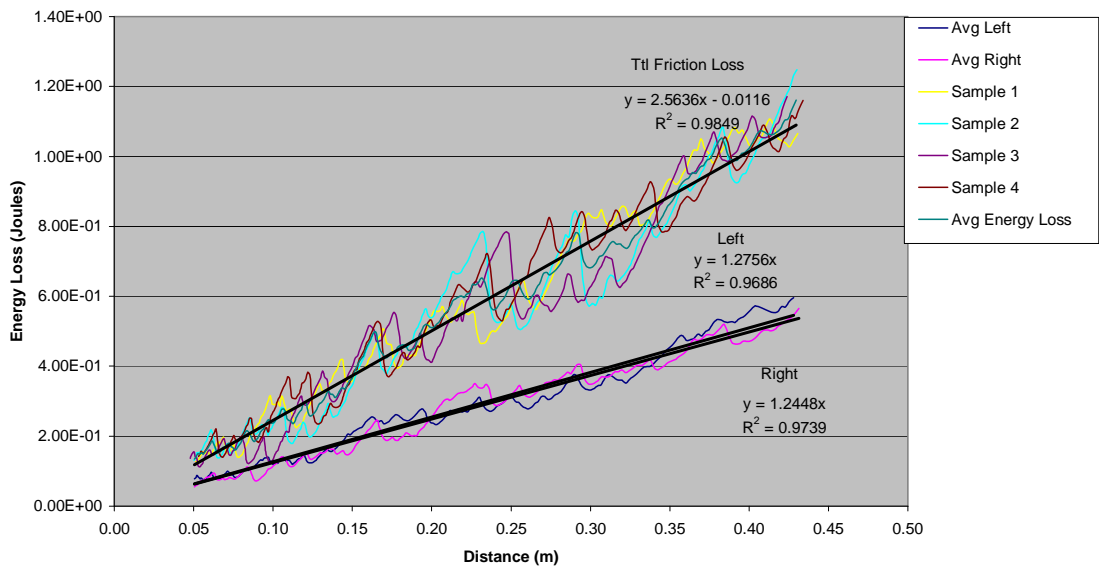
ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550
Counter Weight = 4



FRICTION

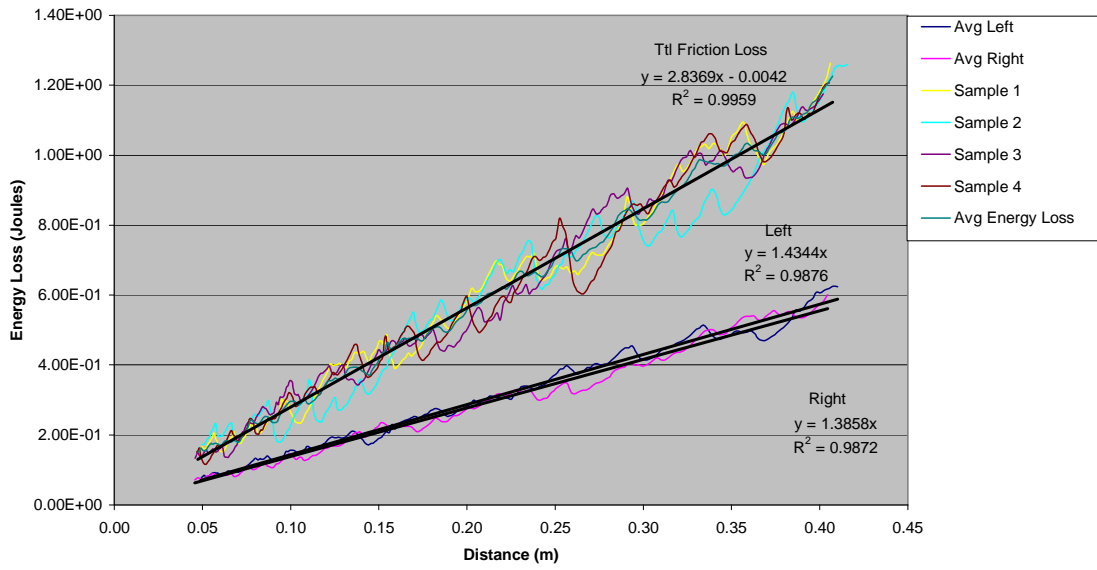
Weight = 550
Paper Weight = 10



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550

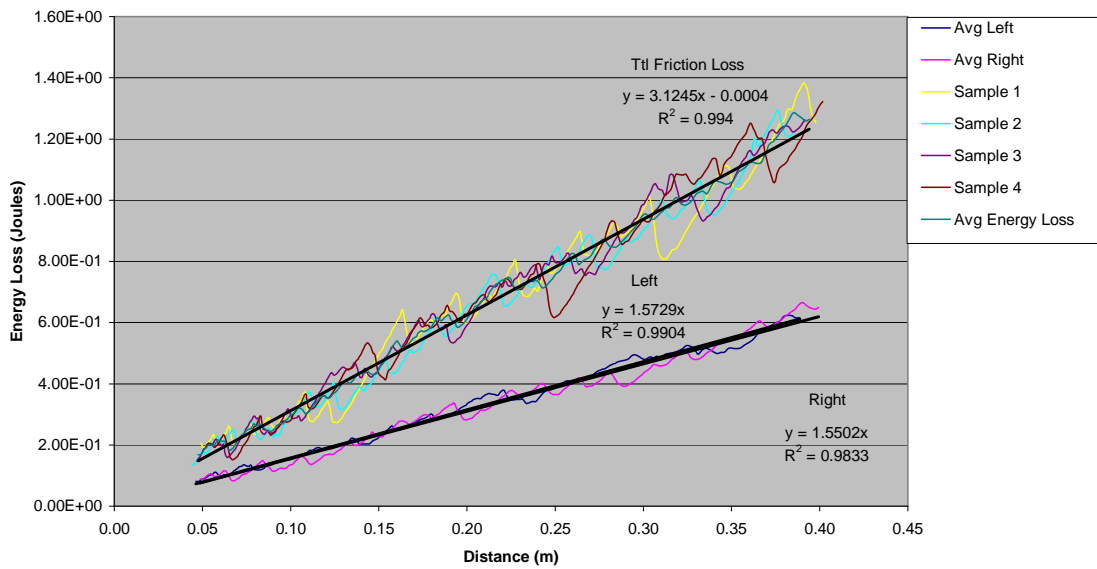
Counter Weight = 20



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550

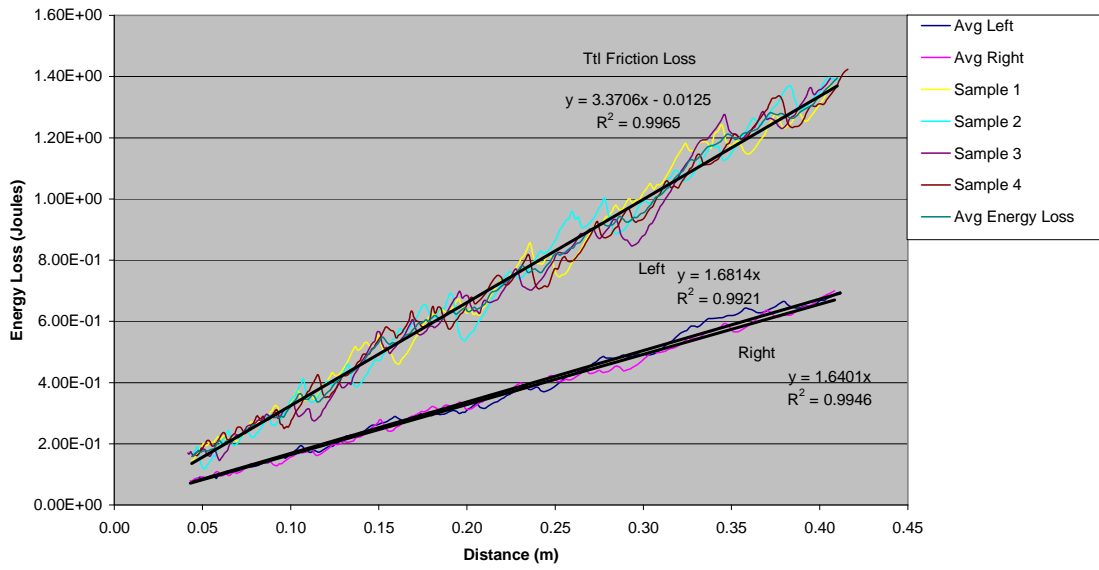
Counter Weight = 30



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550

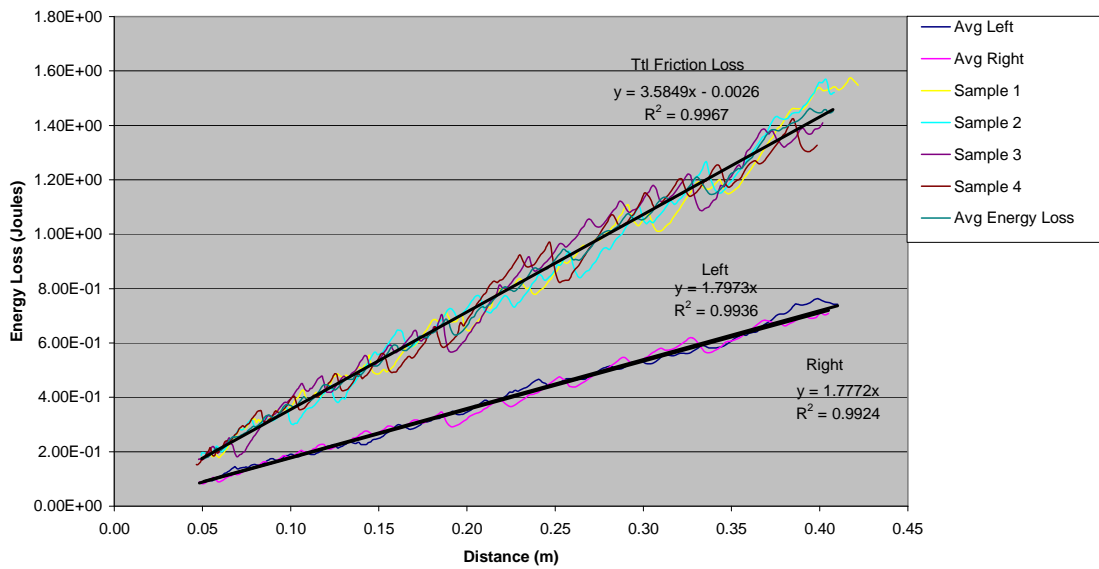
Counter Weight = 40



ENERGY LOSS DUE TO FRICTION

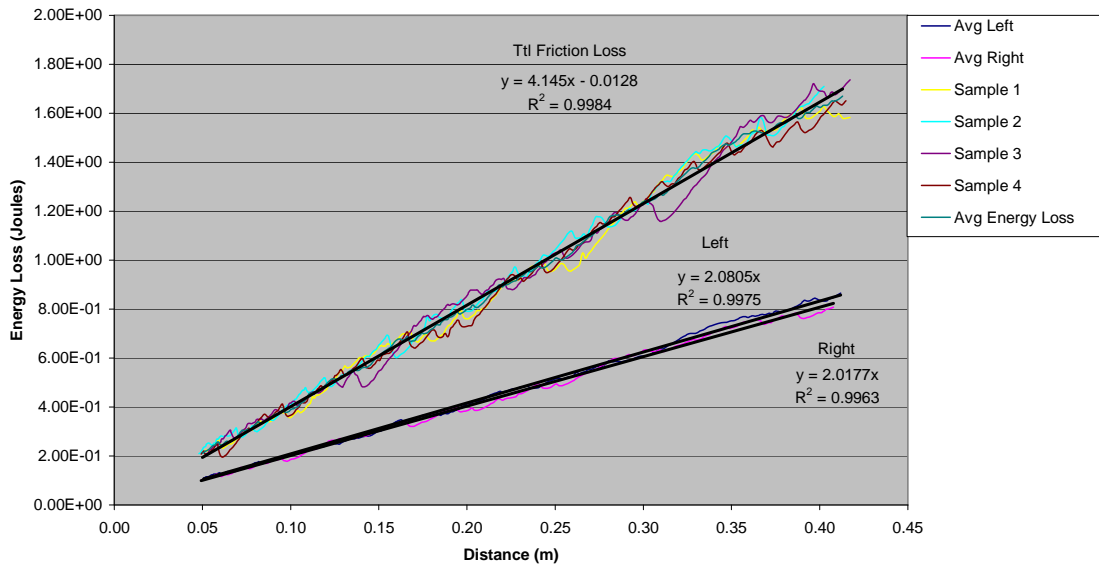
Splitting Weight = 550

Counter Weight = 55



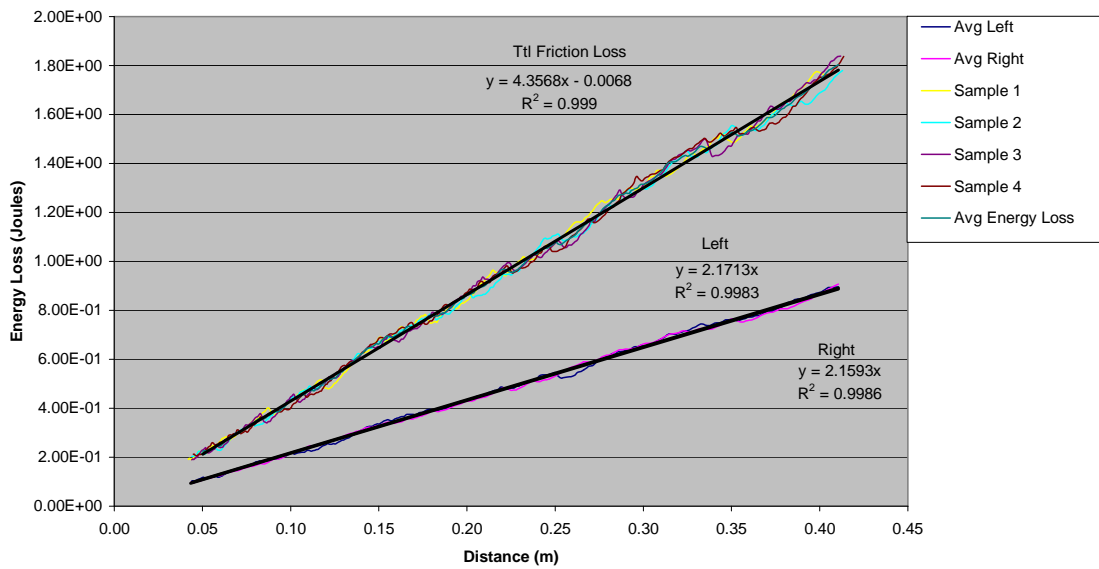
ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550
Counter Weight = 90



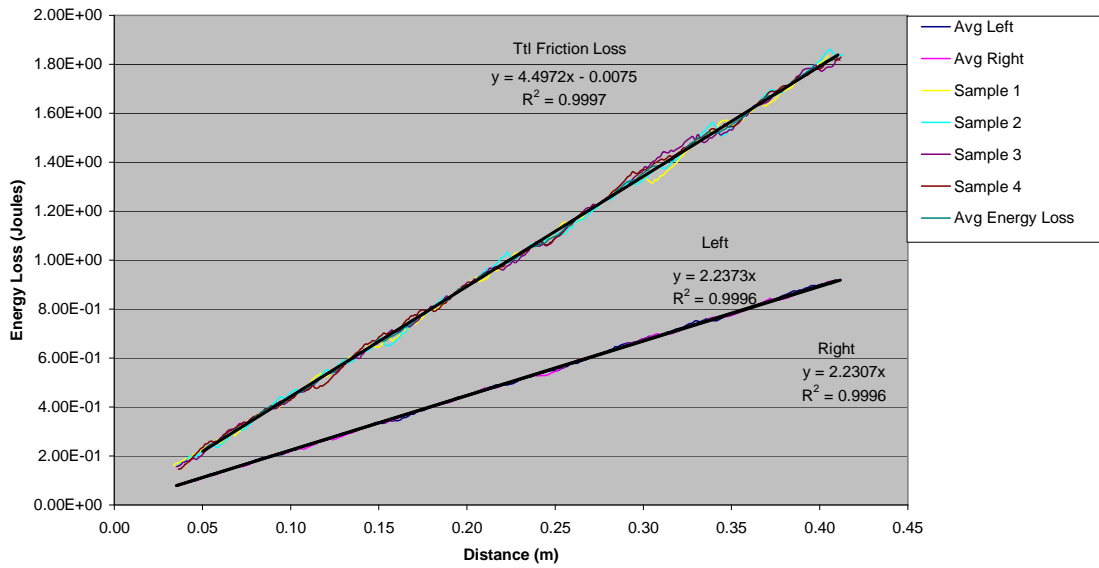
ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550
Counter Weight = 130



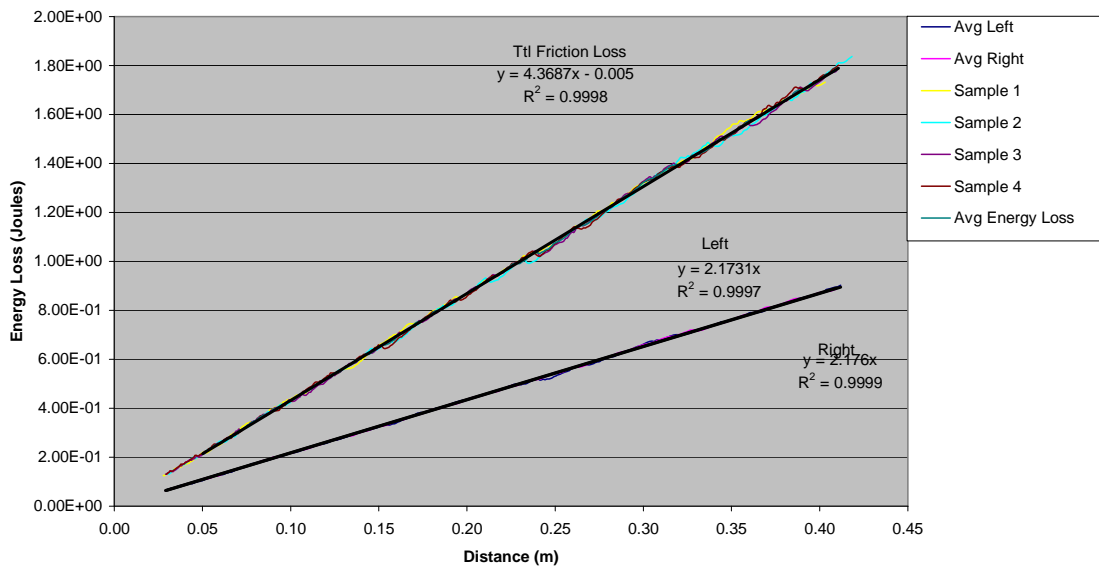
ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550
Counter Weight = 180



ENERGY LOSS DUE TO FRICTION

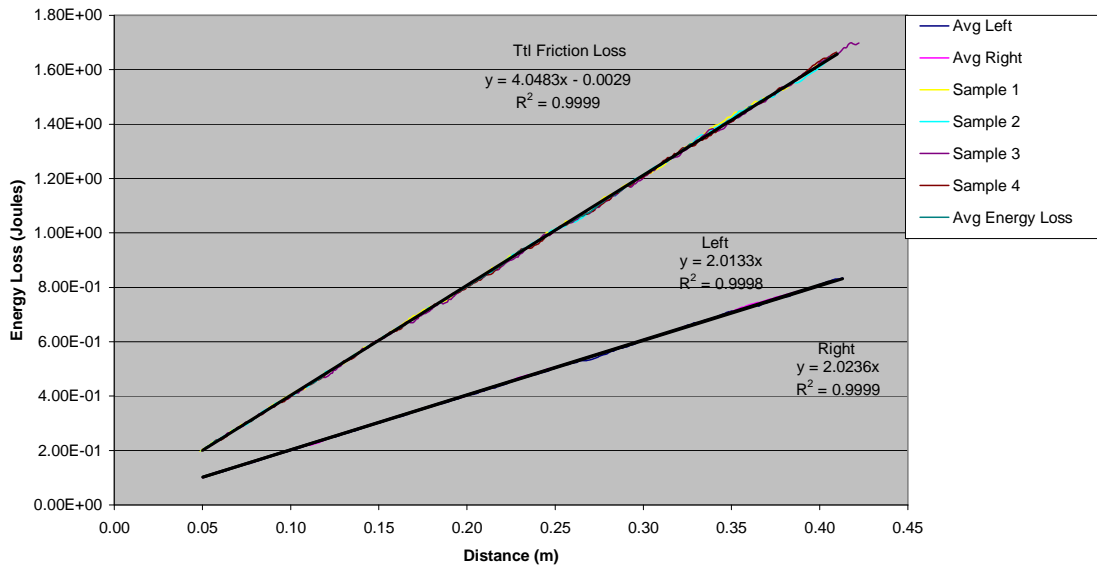
Splitting Weight = 550
Counter Weight = 230



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550

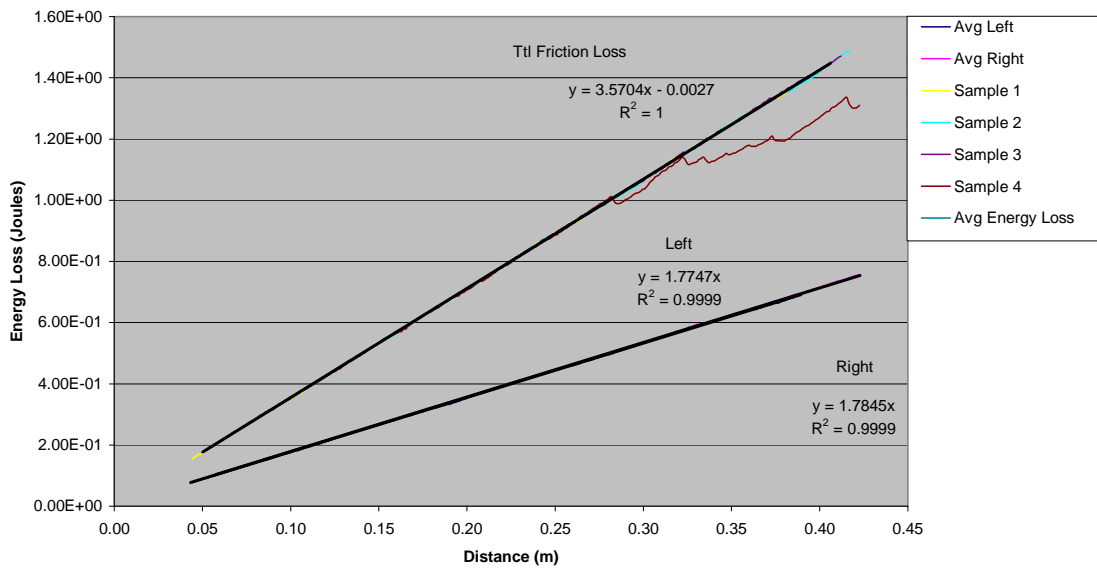
Counter Weight = 280



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550

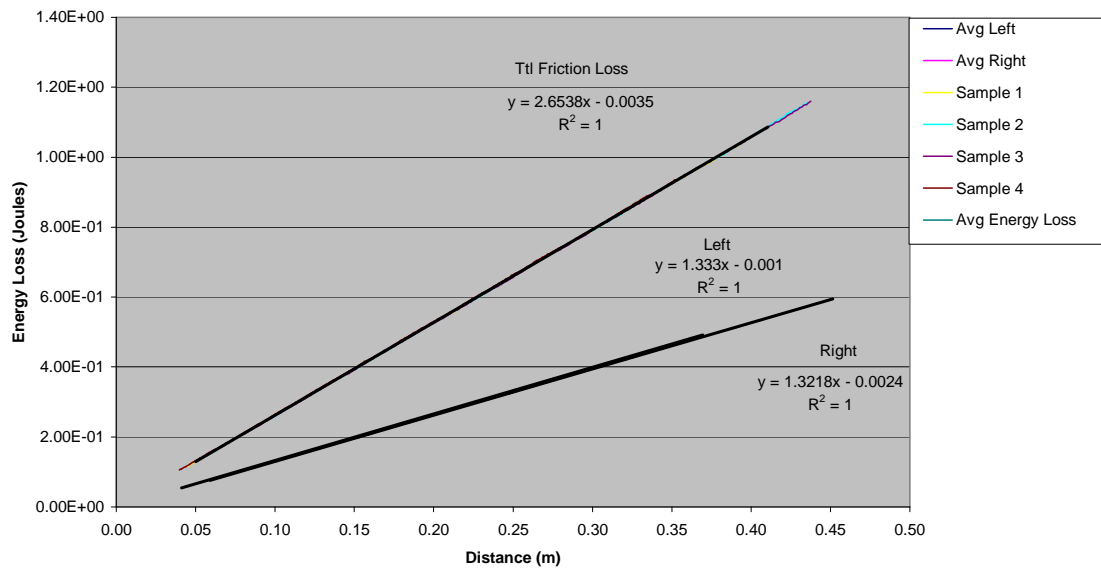
Counter Weight = 330



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 550

Counter Weight = 400



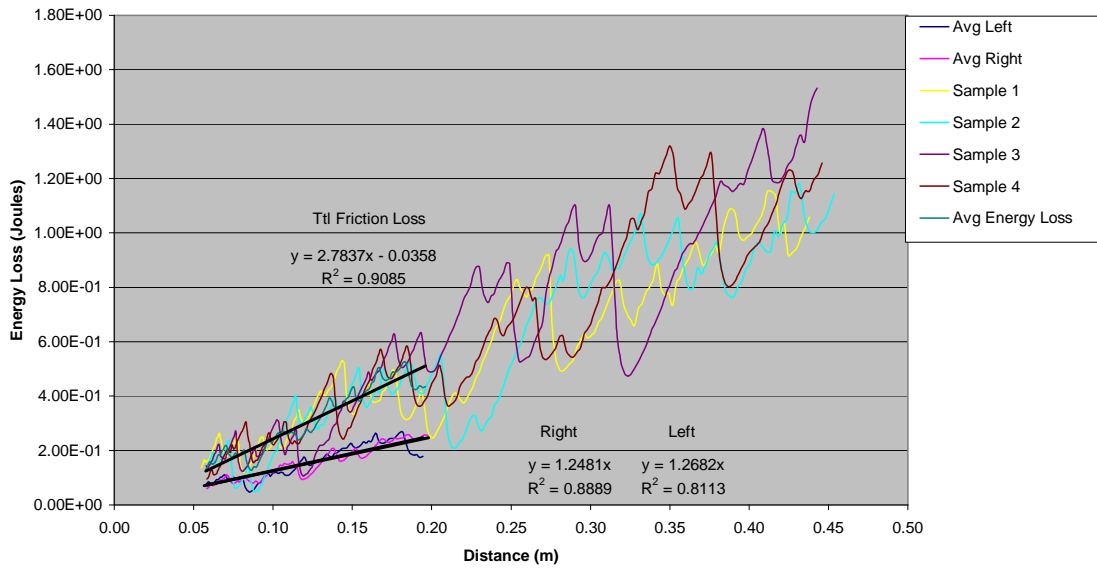
**APPENDIX D: FRICTION ENERGY LOSS VS SPLITTING WEIGHT AND
COUNTER WEIGHT**

Splitting Weight = 770g

ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

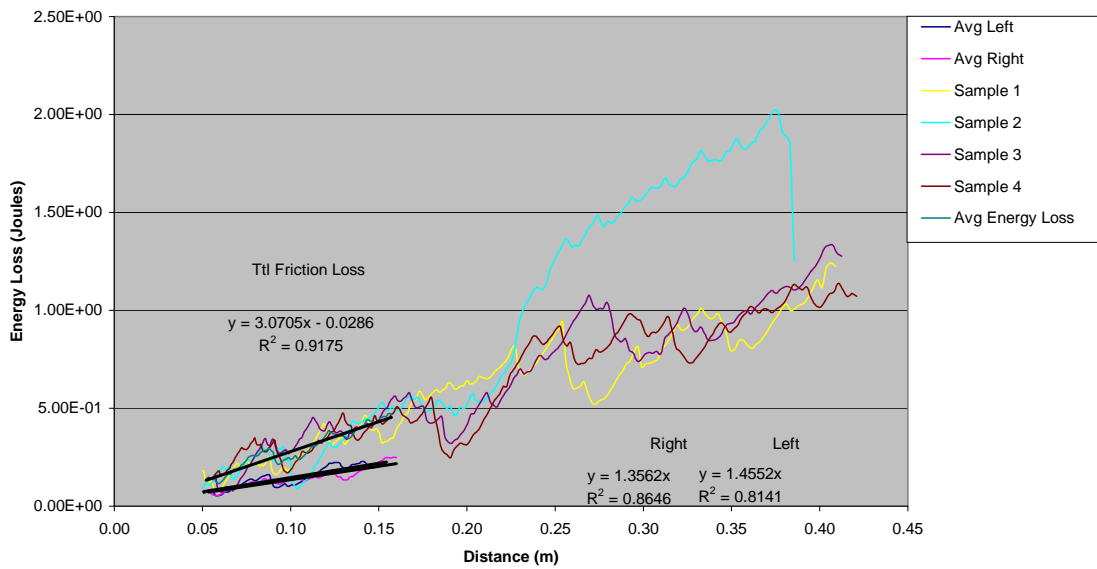
Counter Weight = 4



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

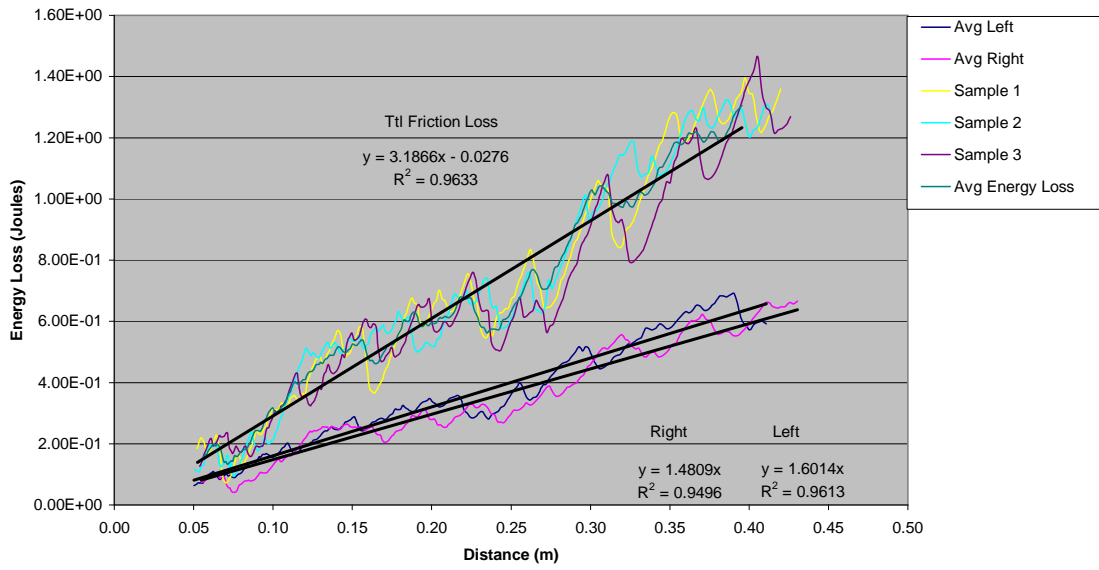
Counter Weight = 10



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

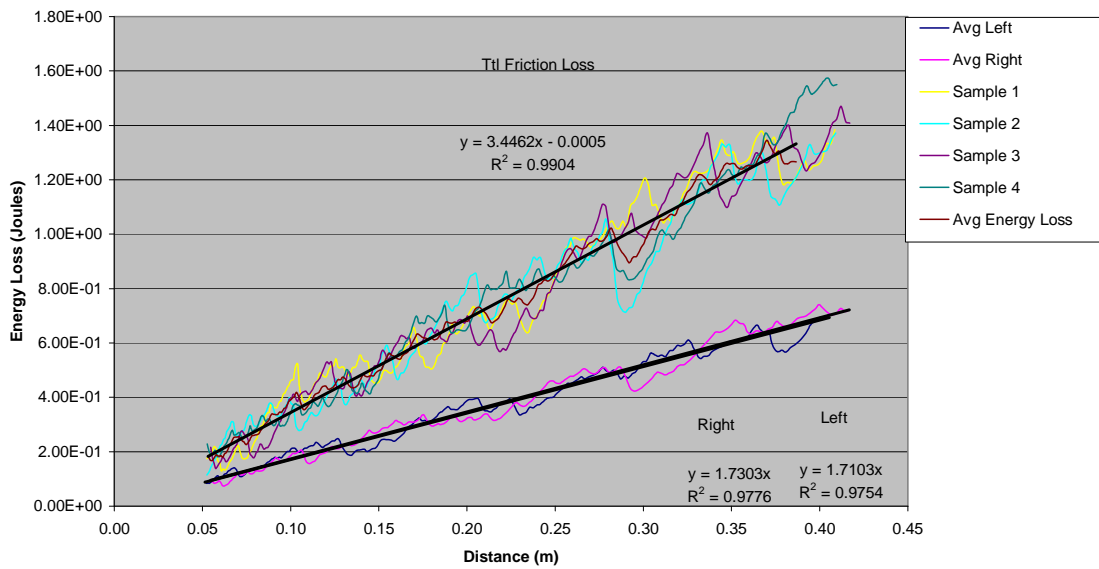
Counter Weight = 20



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

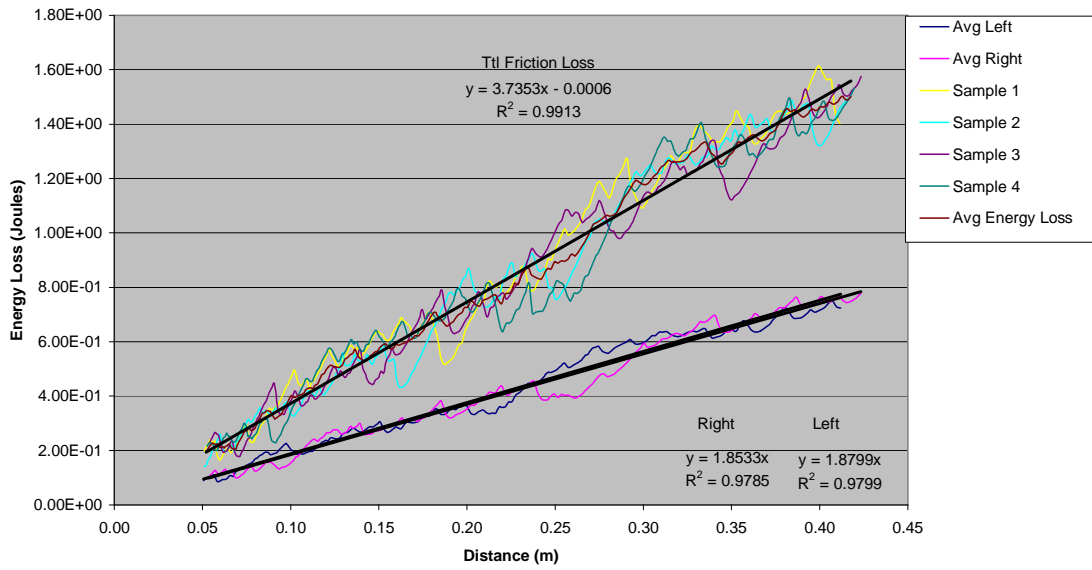
Counter Weight = 30



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

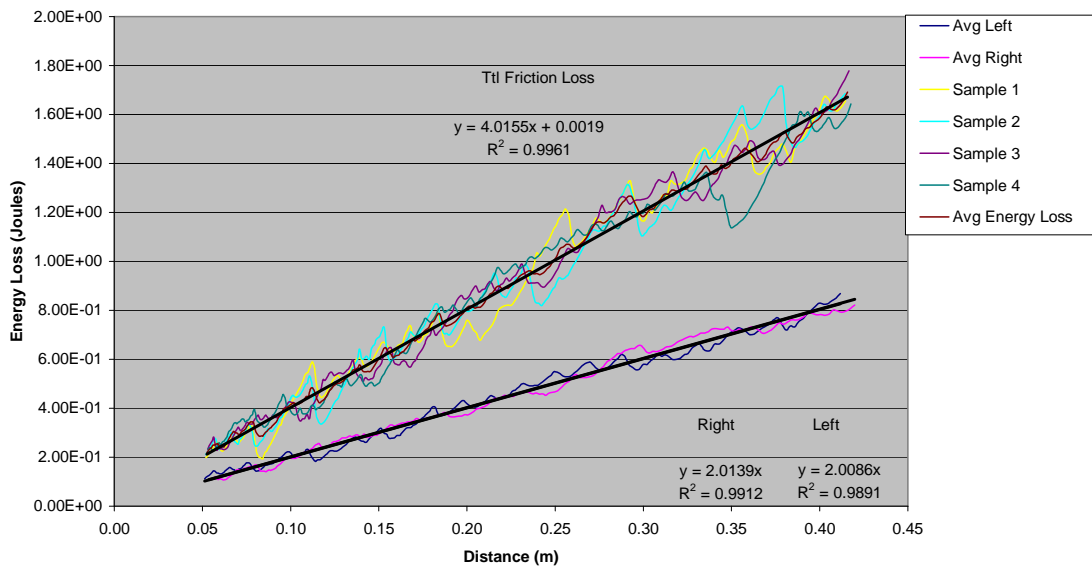
Counter Weight = 40



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

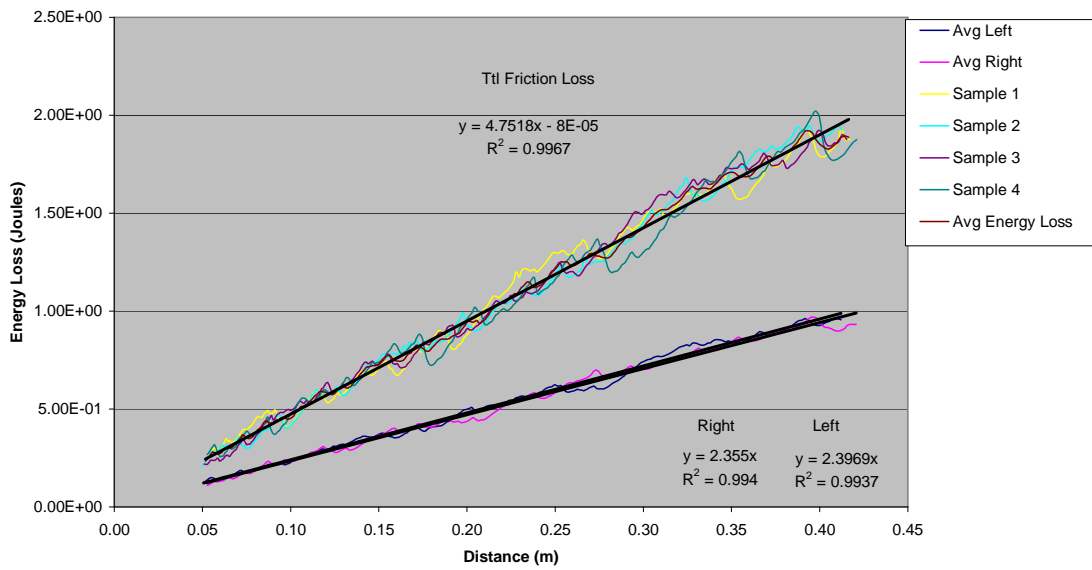
Counter Weight = 55



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

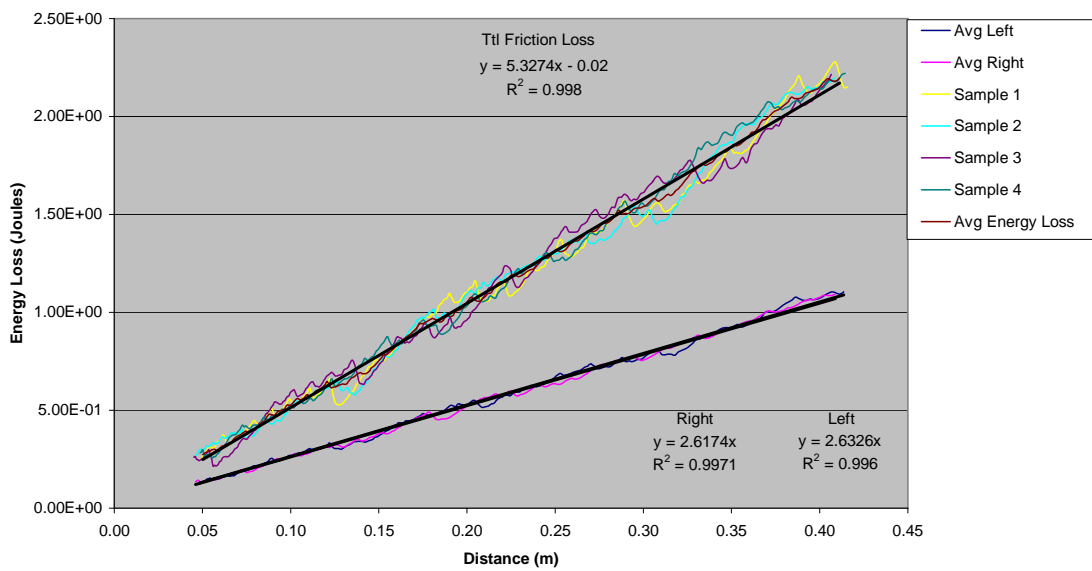
Counter Weight = 90



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

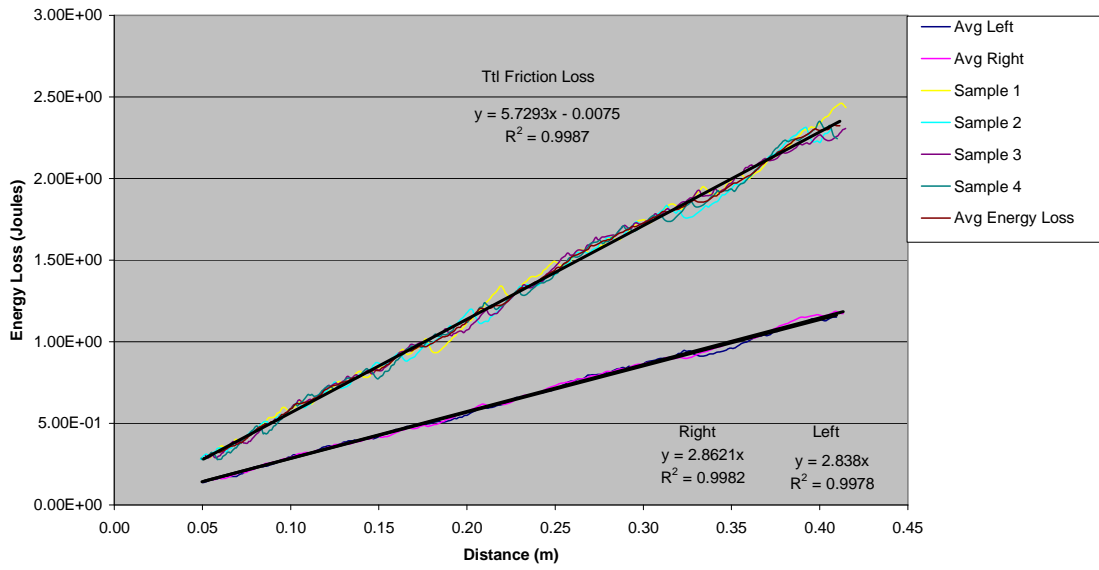
Counter Weight = 130



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

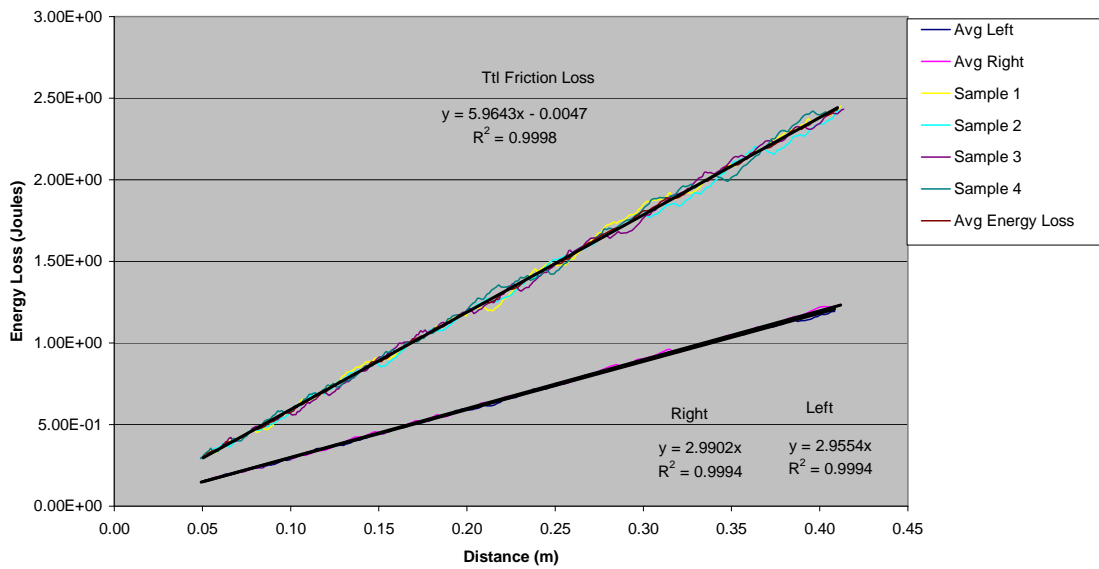
Counter Weight = 180



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

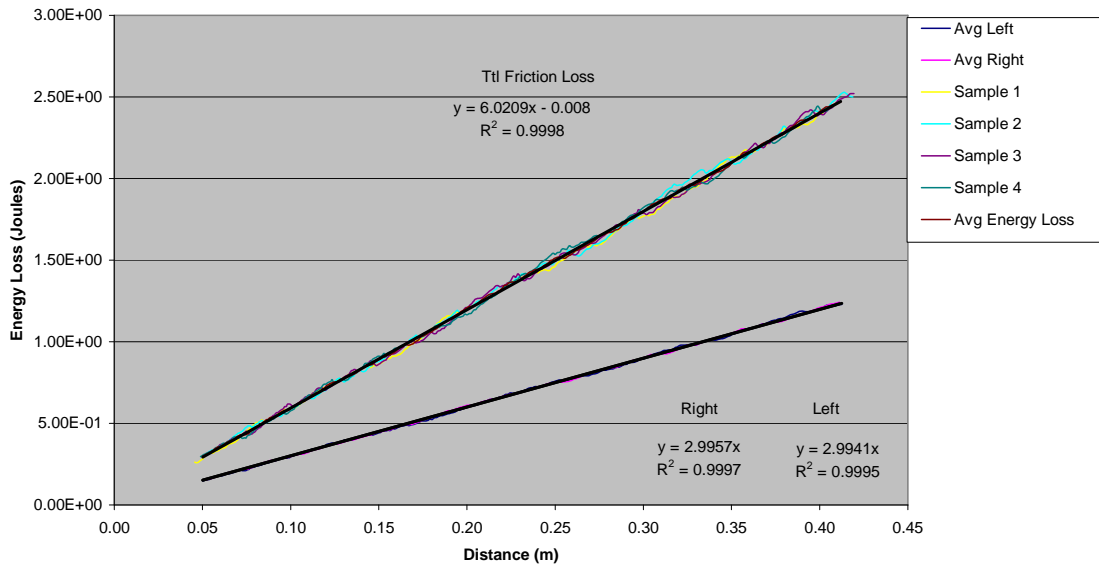
Counter Weight = 230



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

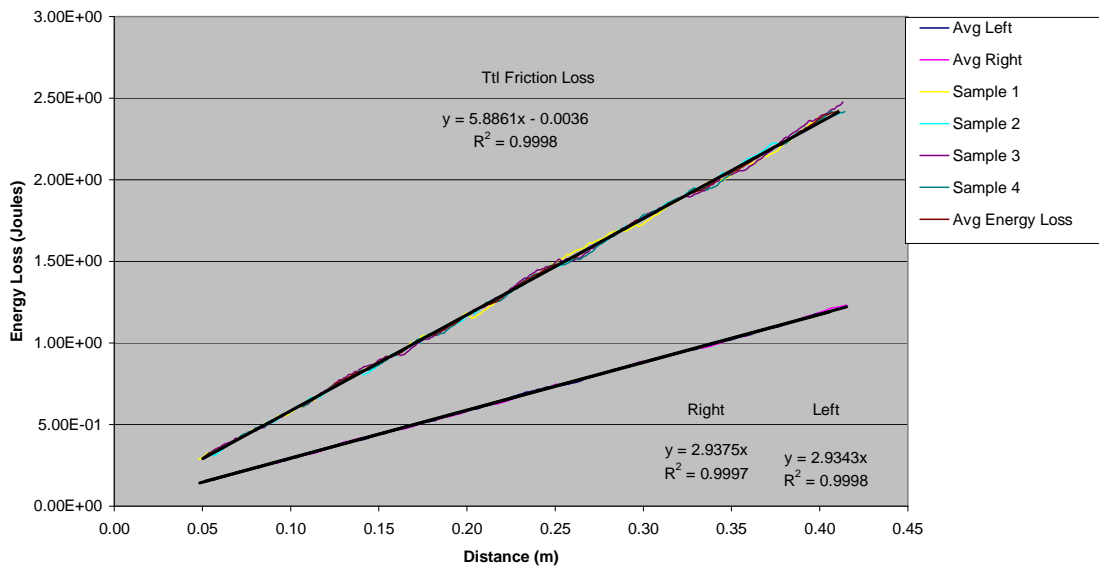
Counter Weight = 280



ENERGY LOSS DUE TO FRICTION

Splitting Weight = 770

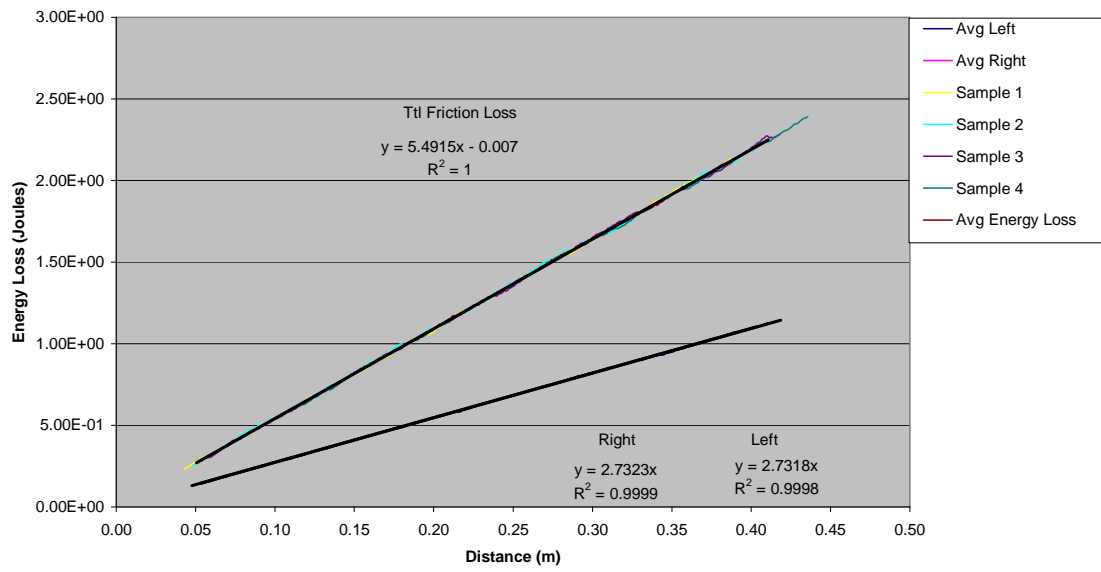
Counter Weight = 330



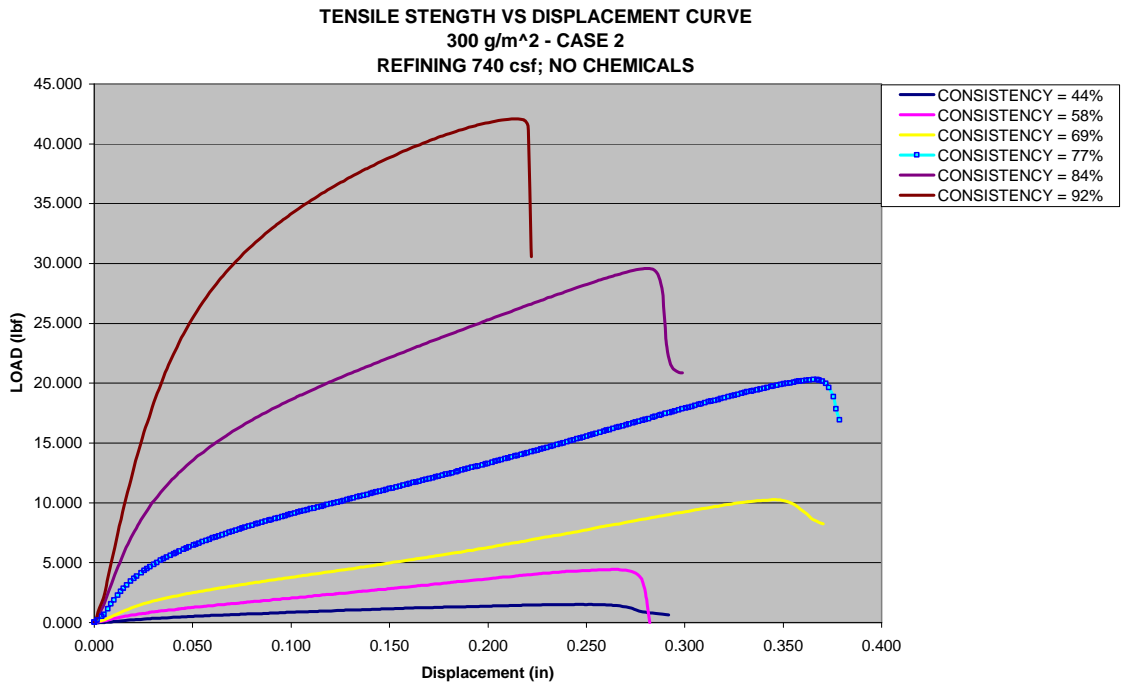
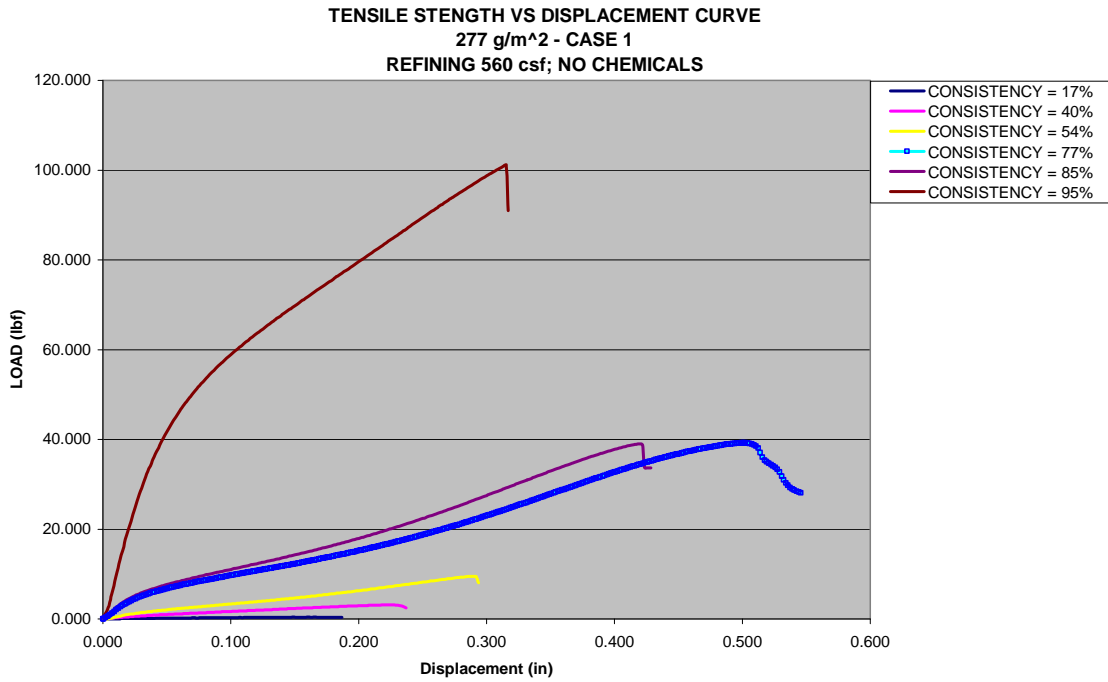
ENERGY LOSS DUE TO FRICTION

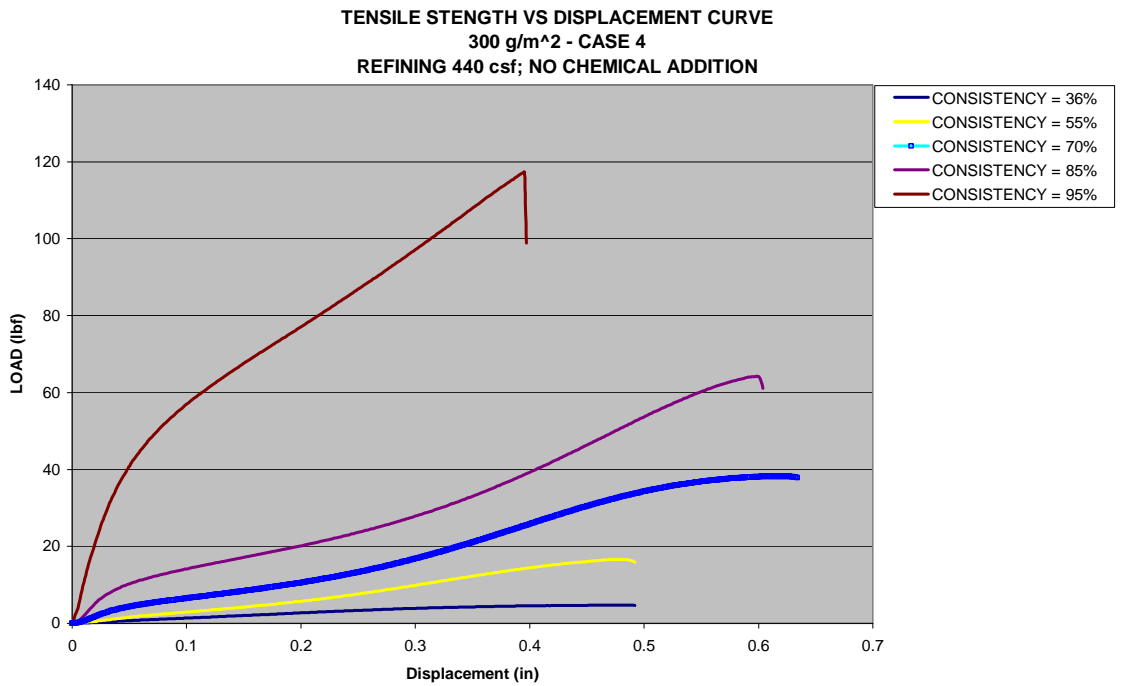
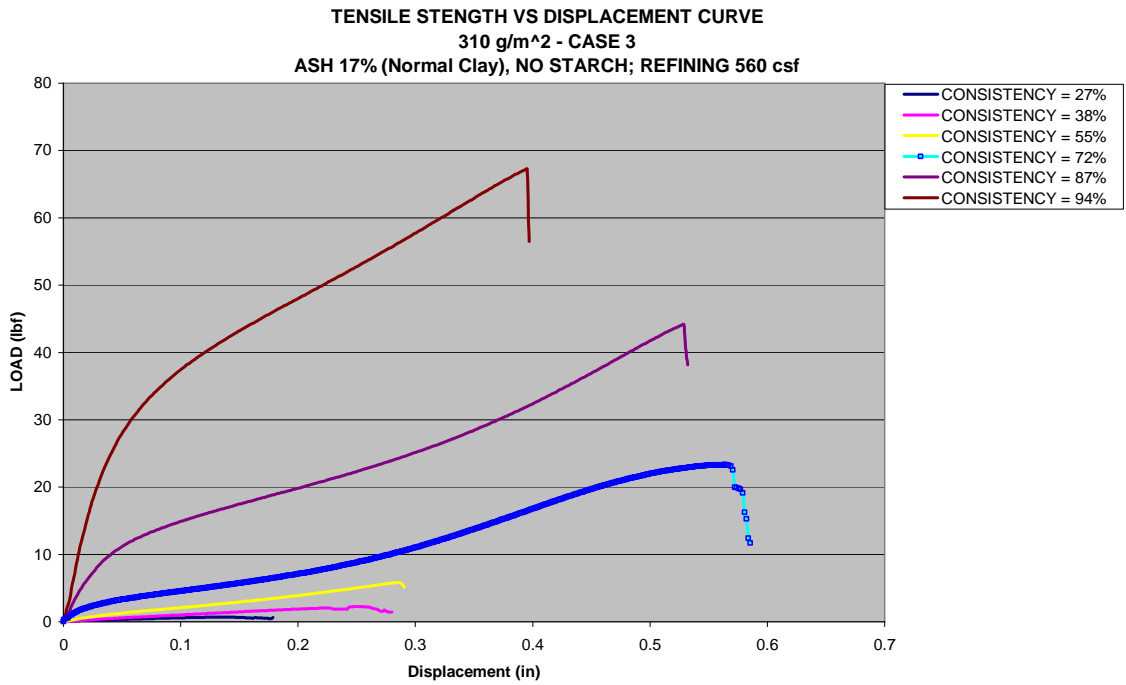
Splitting Weight = 770

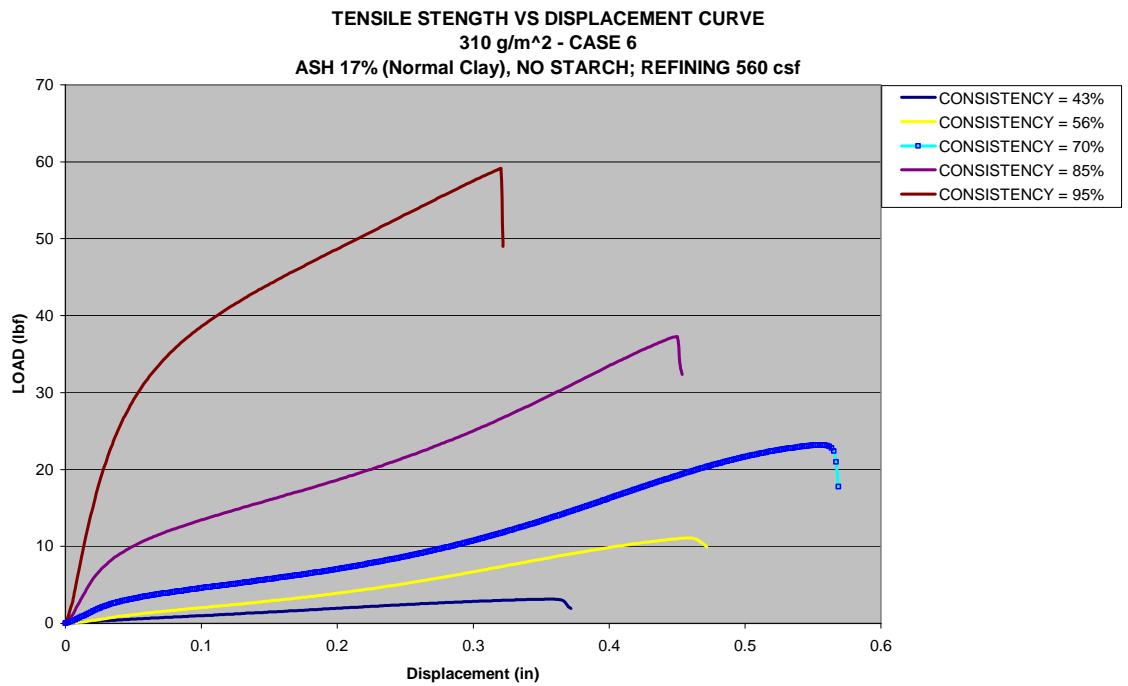
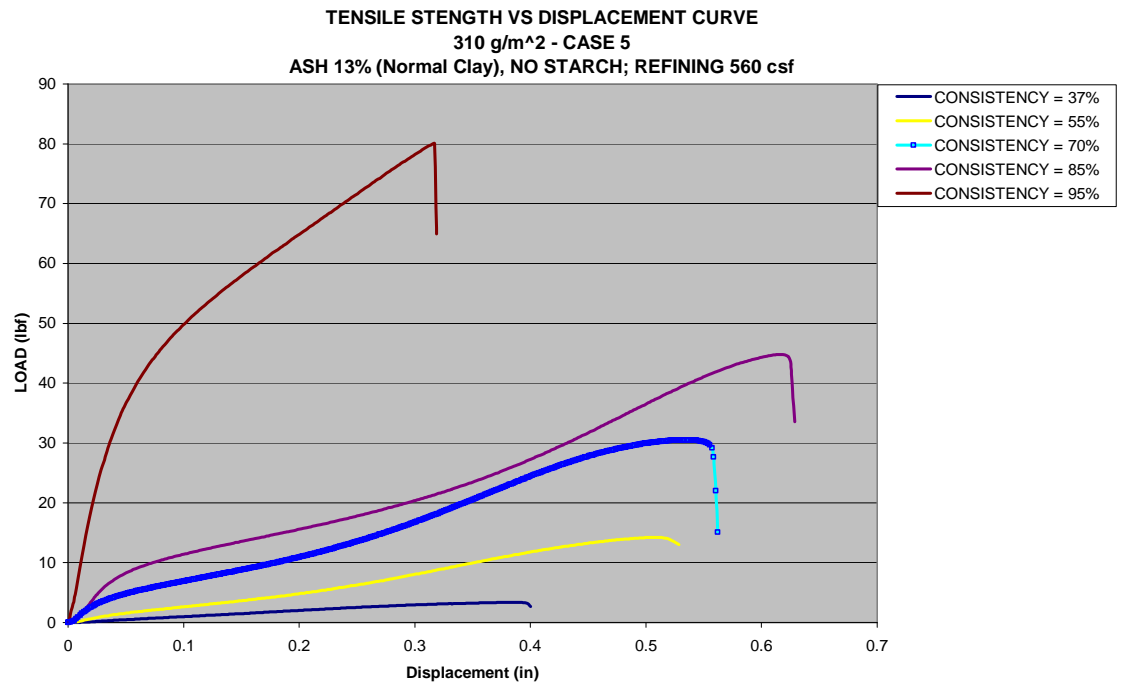
Counter Weight = 400

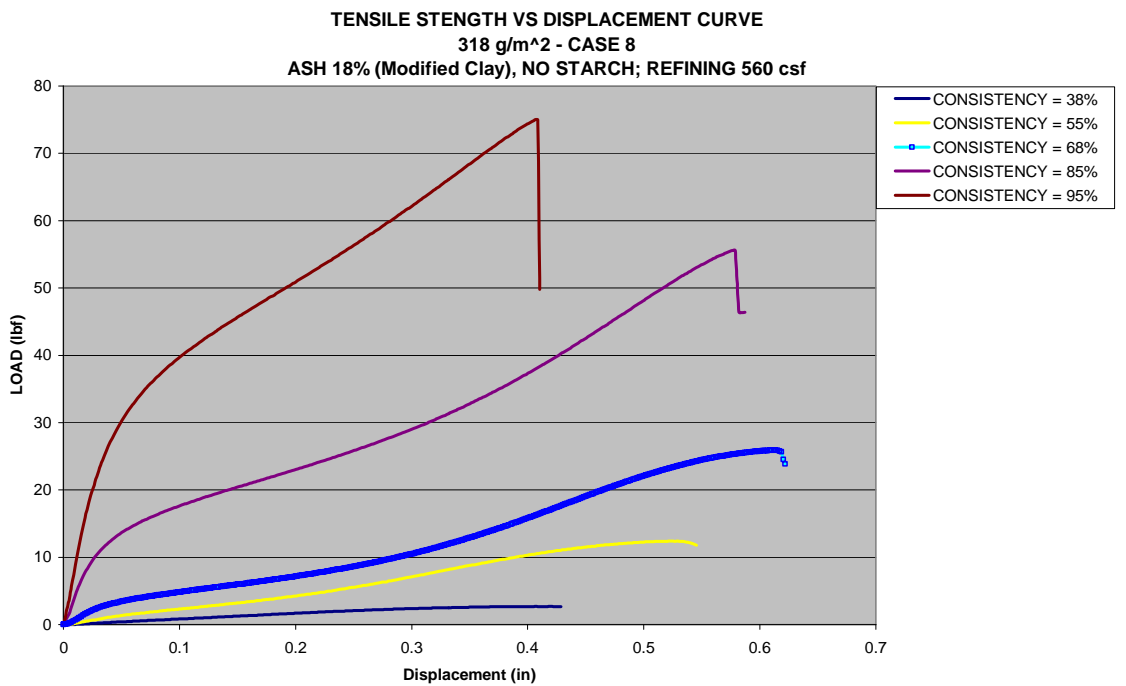
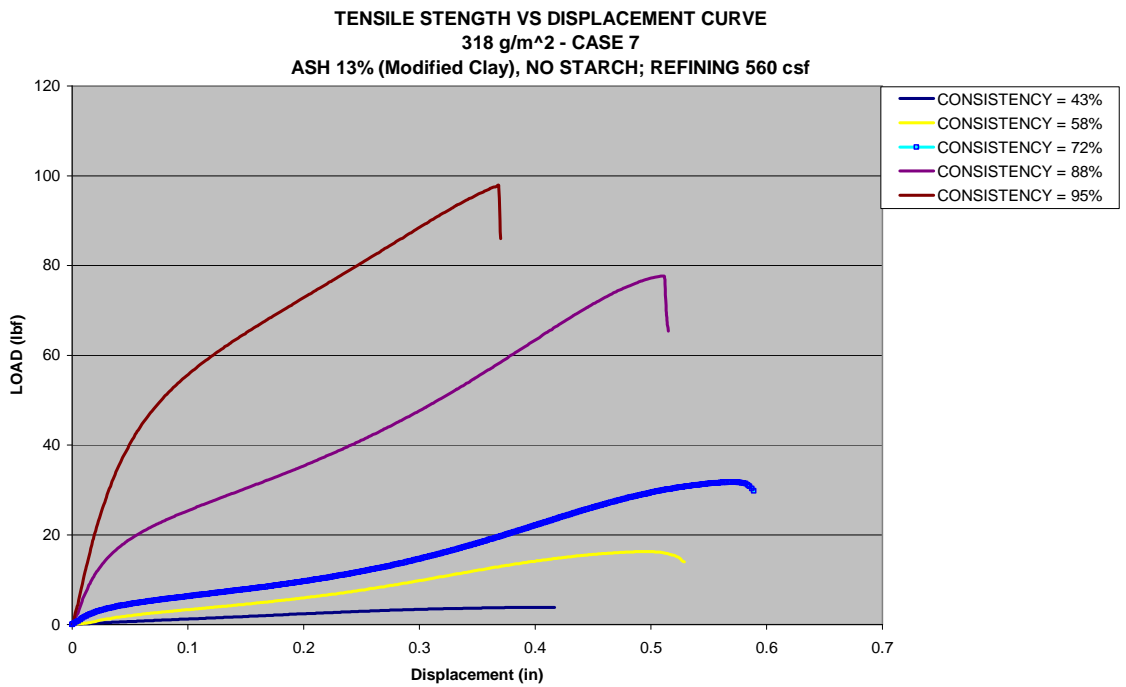


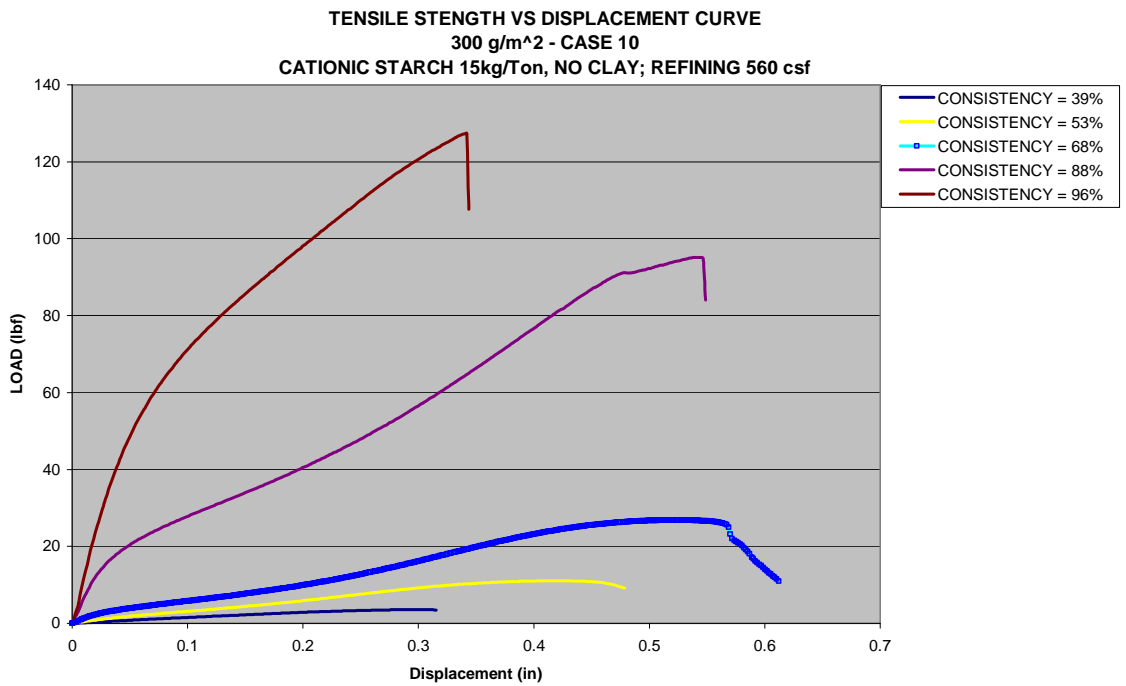
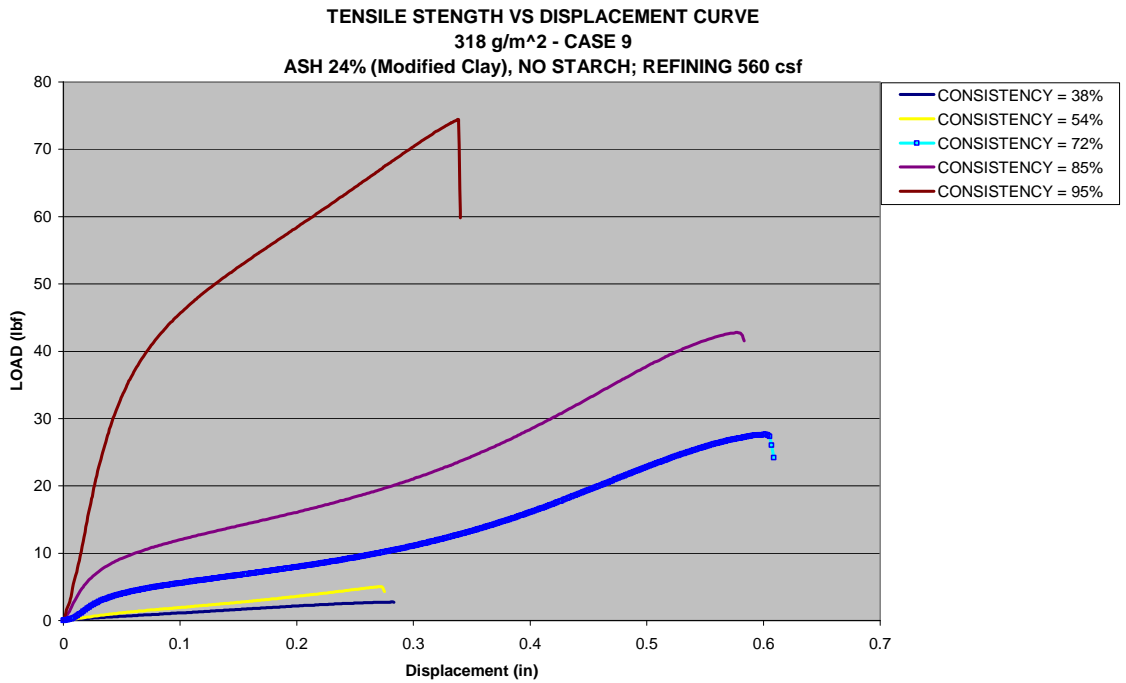
APPENDIX E.1: STRESS – STRAIN CURVES

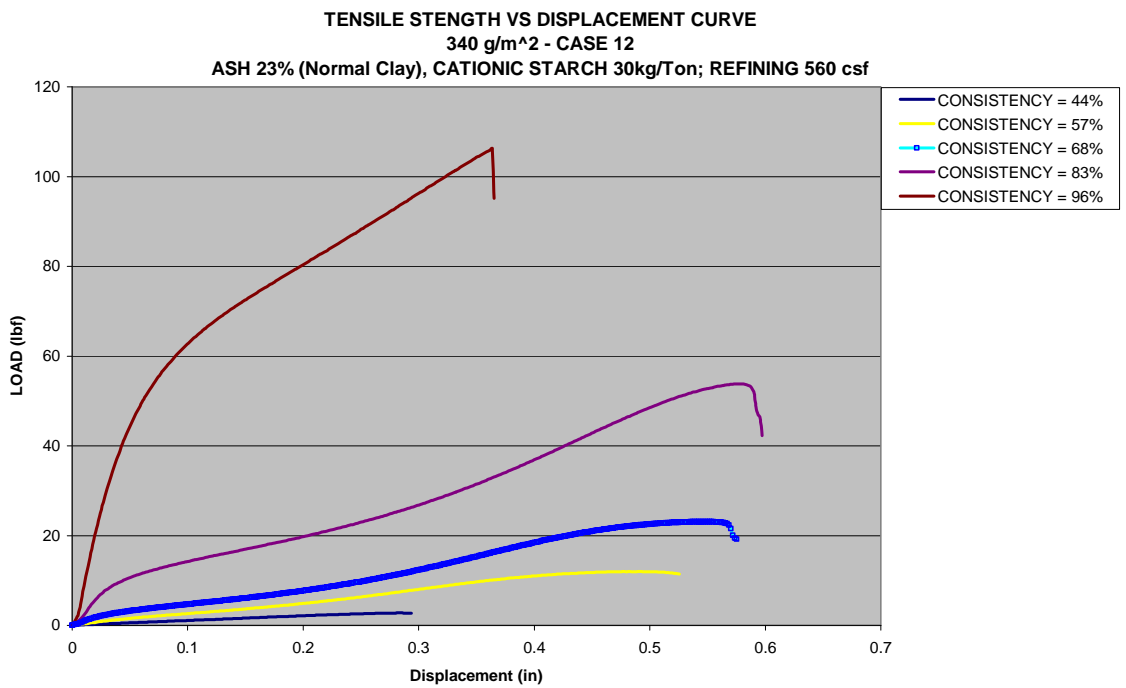
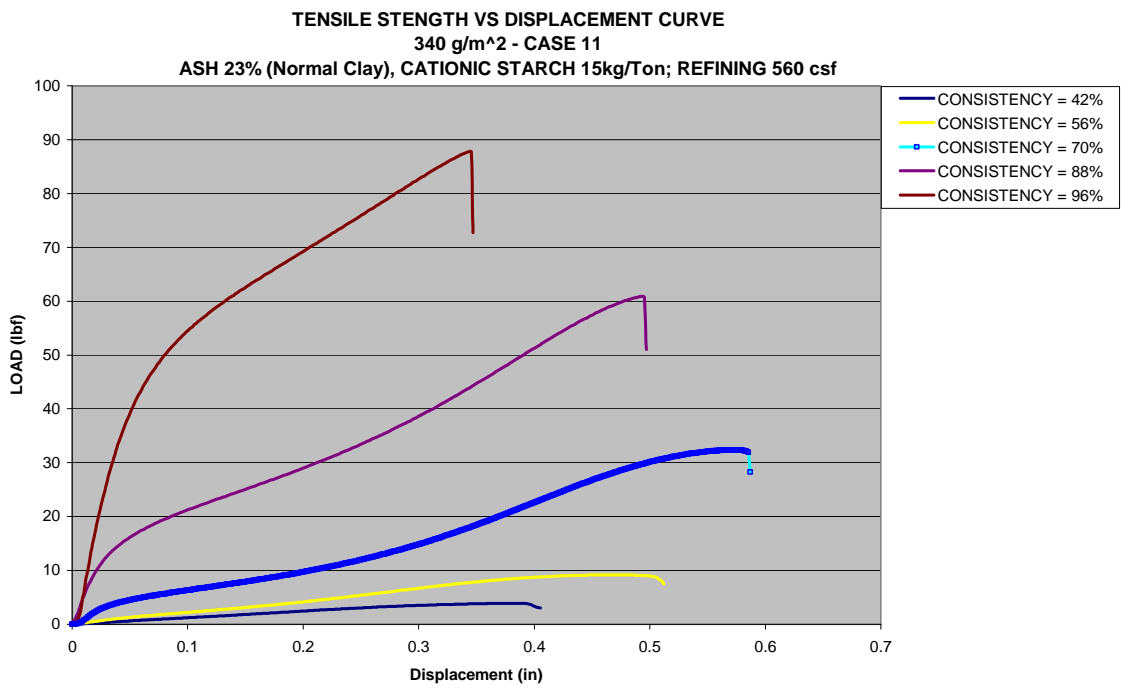




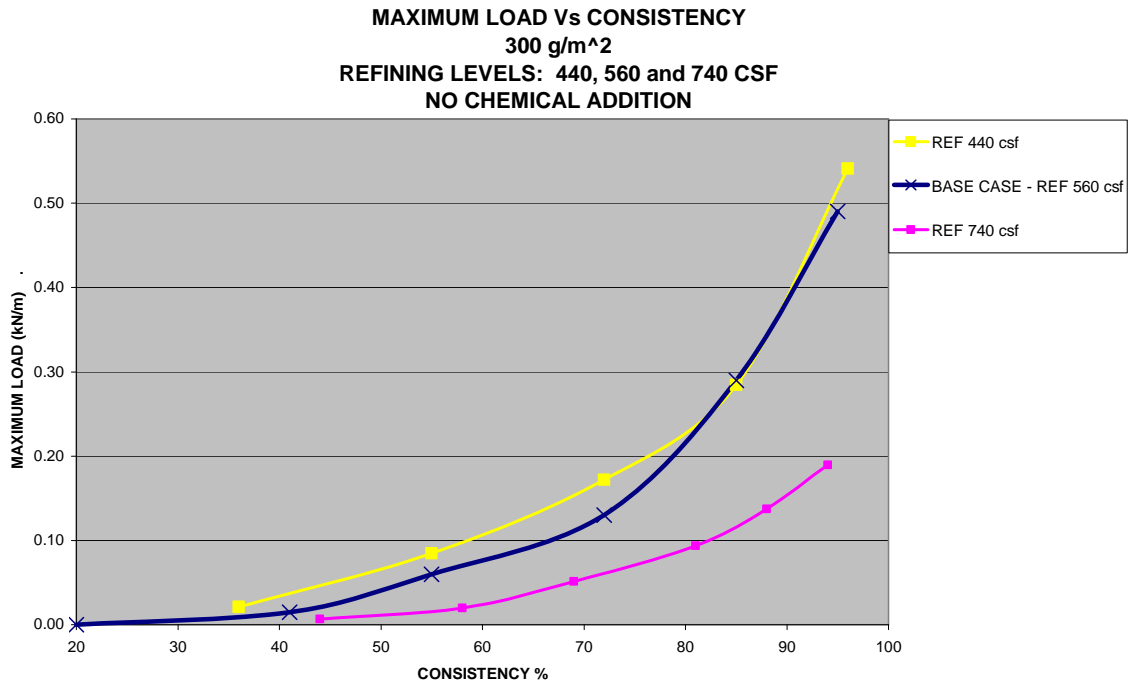
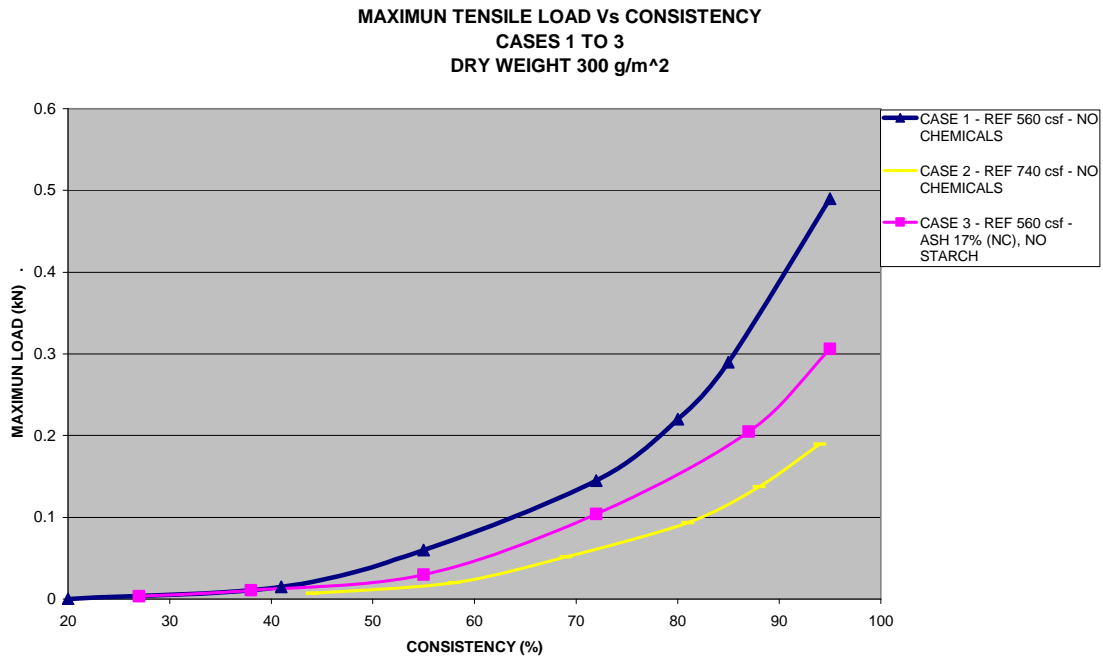


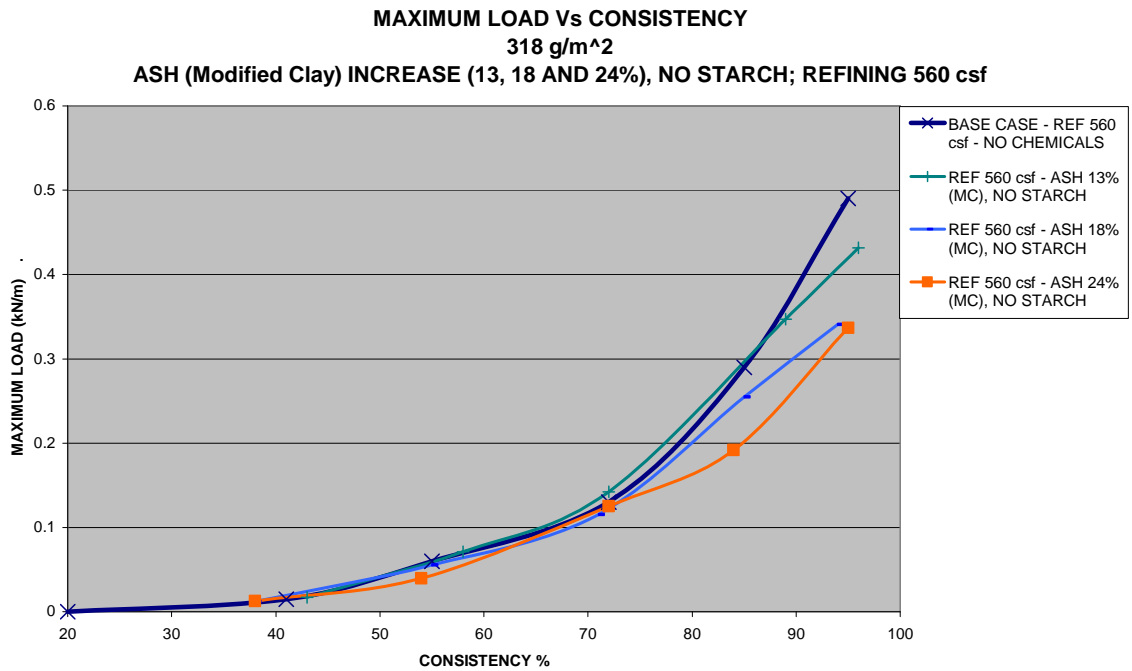
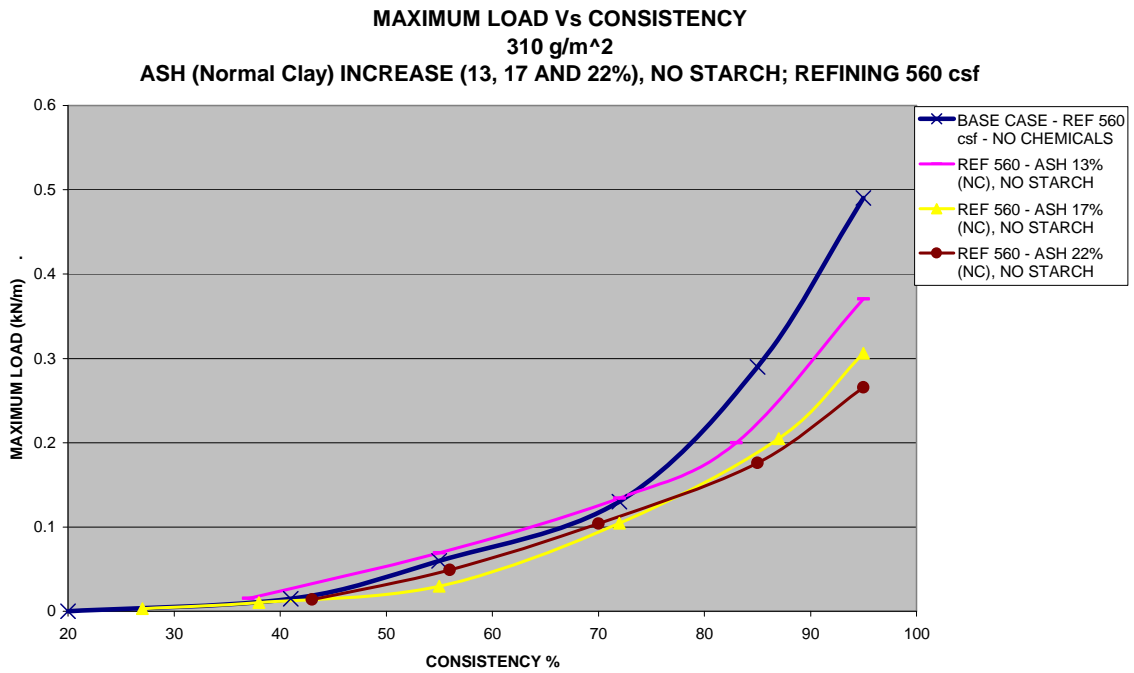




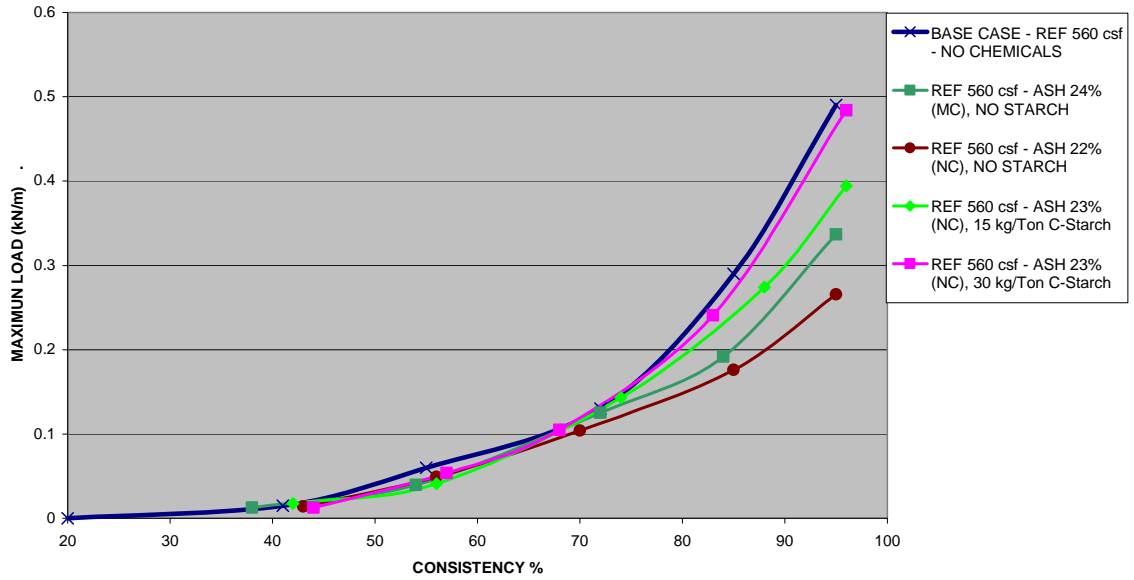


APPENDIX E.2: TENSILE STRENGTH VS SOLIDS

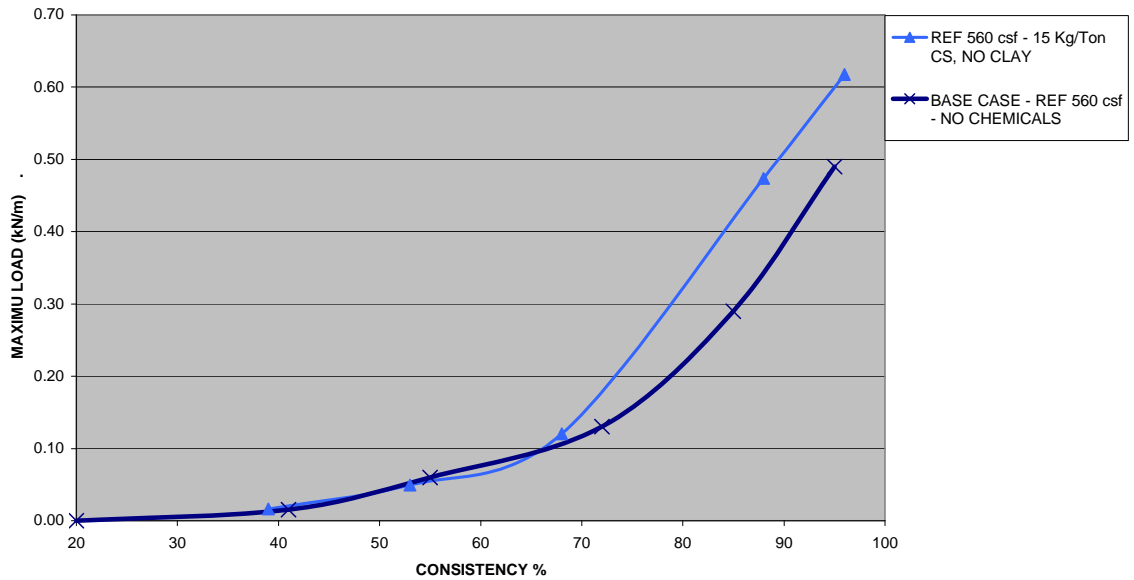




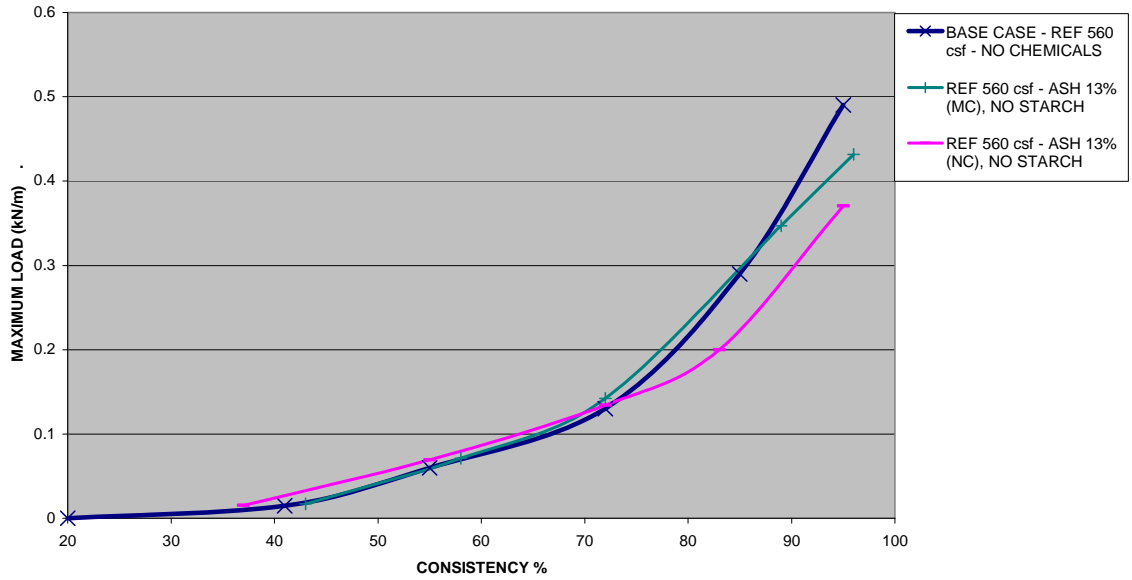
MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay); 318 g/m² (Modified Clay); 340 g/m² (Normal Clay & C-Starch)
ASH CONTENT 23%; REFINING 560 csf



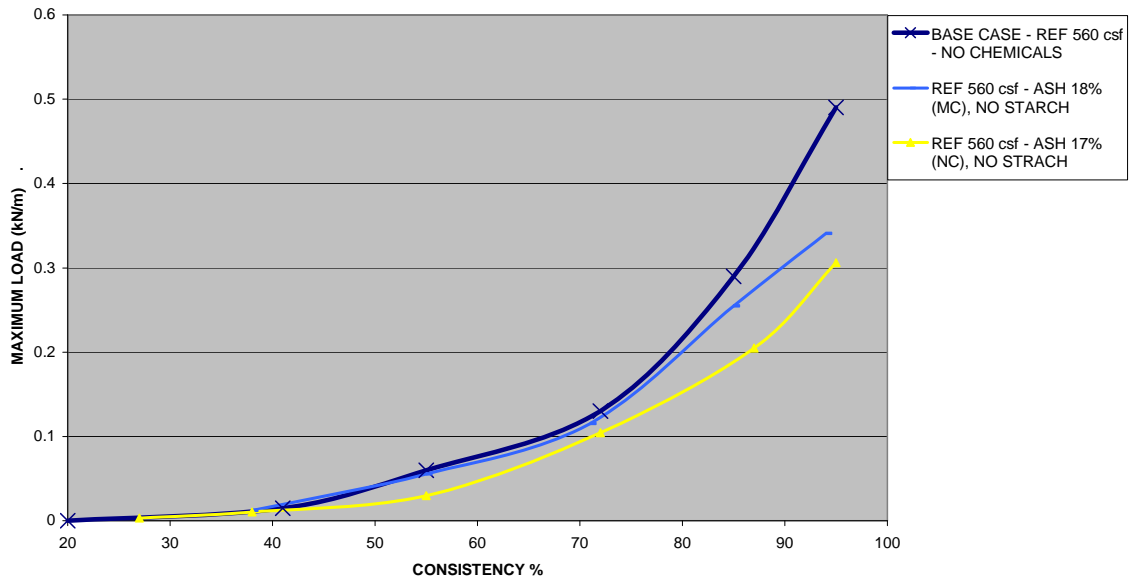
MAXIMU LOAD Vs CONSISTENCY
BASE CASE VS BASE CASE + 15 kg/Ton C-STARCH; NO CLAY
300 g/m²



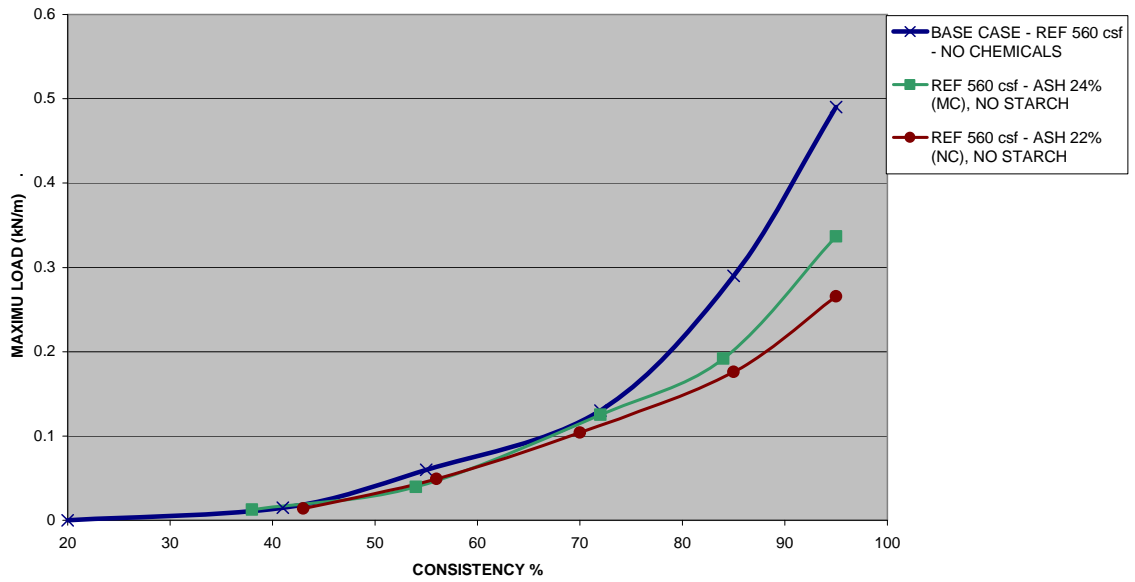
MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay) & 318 g/m² (Modified Clay)
ASH CONTENT 13%, NO STARCH; REFINING 560 csf



MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay) & 318 g/m² (Modified Clay)
ASH CONTENT 17%, NO STARCH; REFINING 560 csf

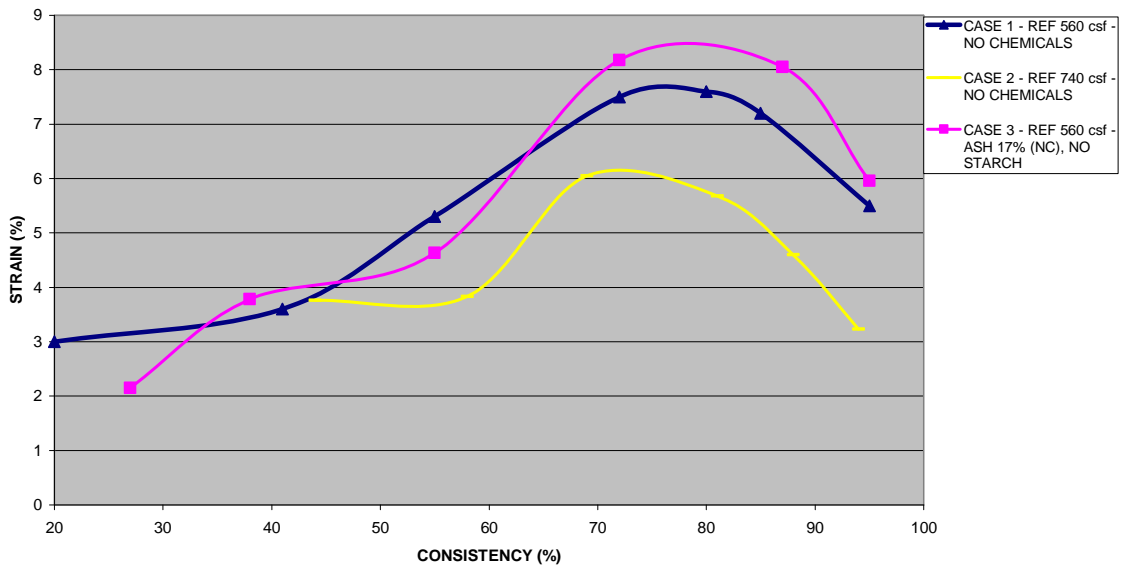


MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay) & 318 g/m² (Modified Clay)
ASH CONTENT 23%, NO STARCH; REFINING 560 csf

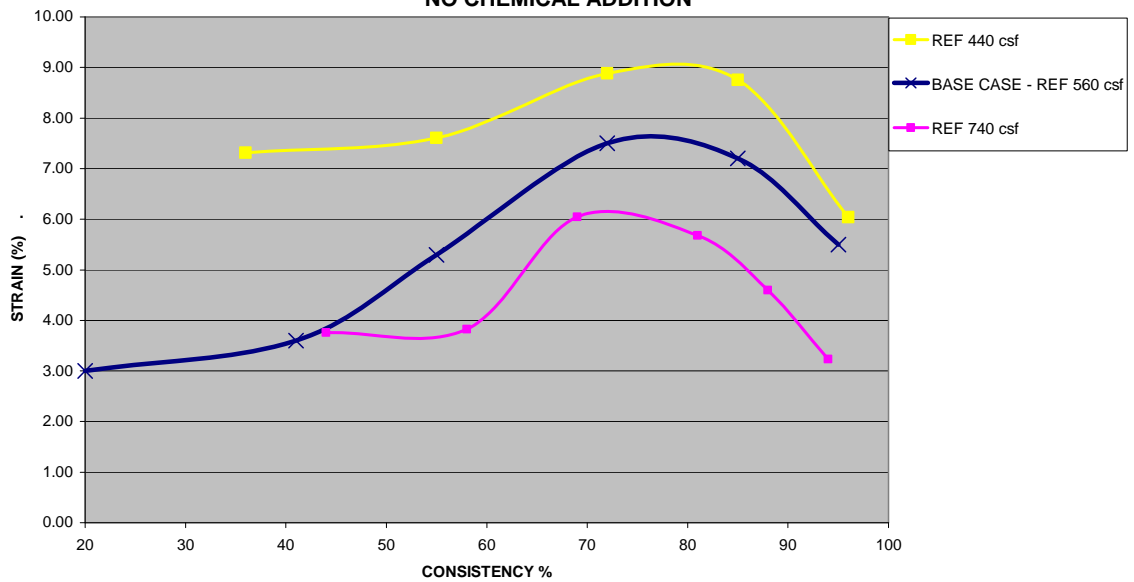


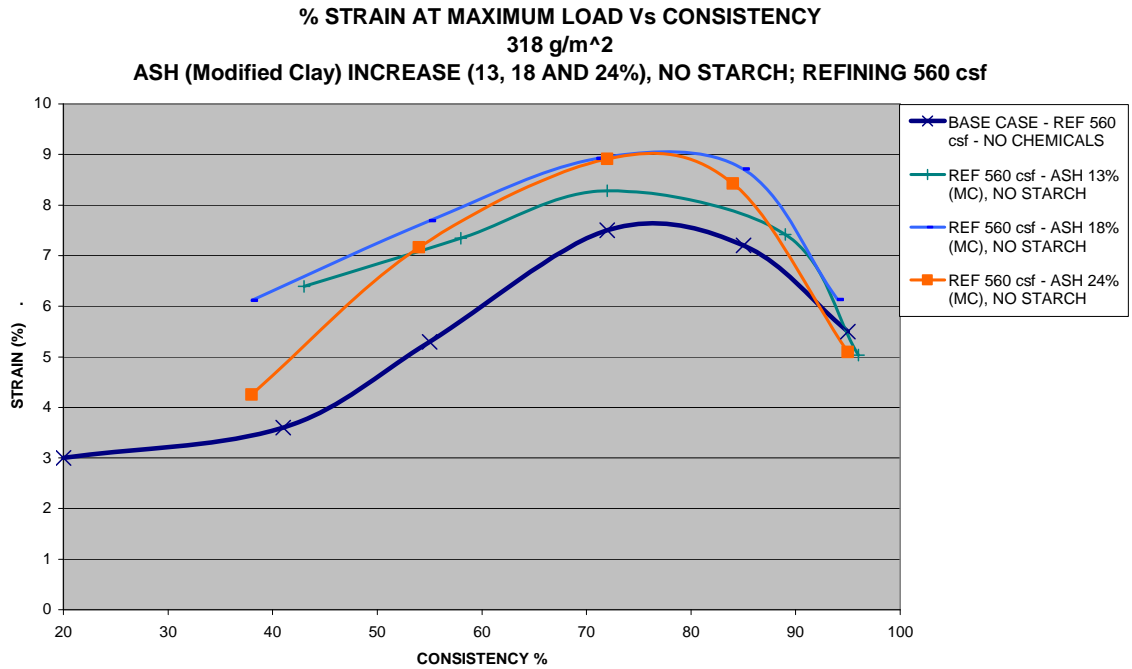
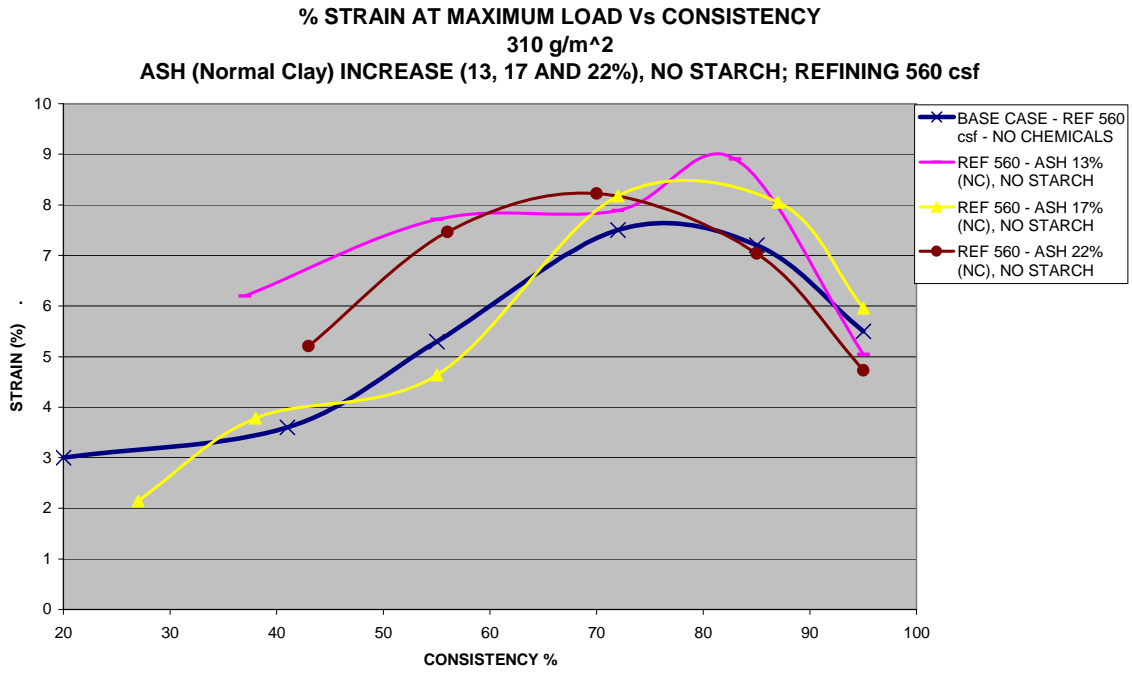
APPENDIX E.3: TENSILE STRAIN VS SOLIDS

% STRAIN AT MAXIMUN TENSILE LOAD Vs CONSISTENCY
CASES 1 TO 3
DRY WEIGHT 300 g/m²

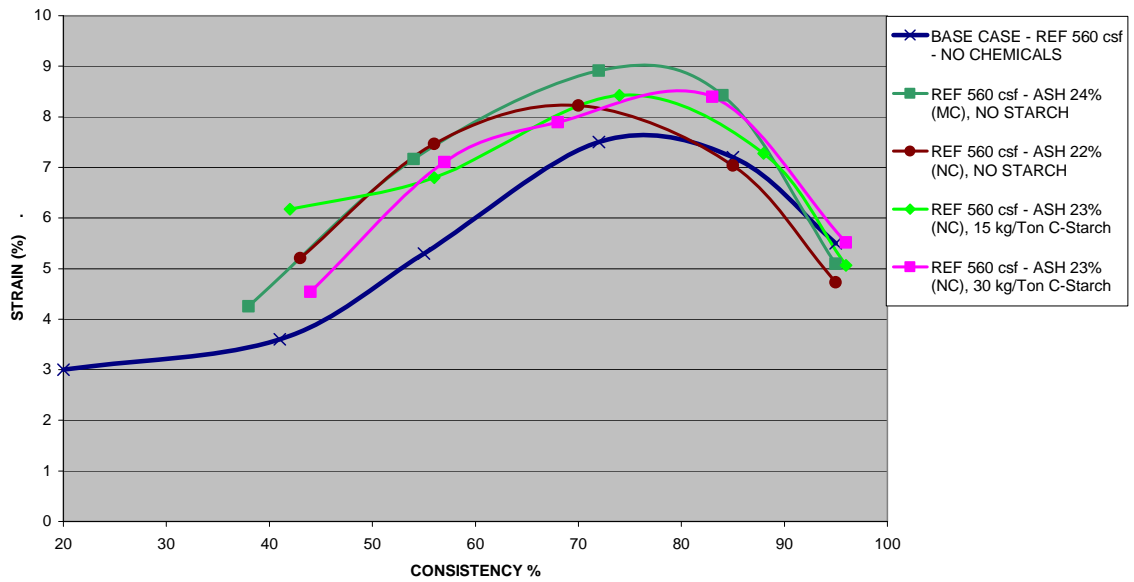


% STRAIN AT MAXIMUM LOAD Vs CONSISTENCY
300 g/m²
REFINING LEVELS: 440, 560 and 740 CSF
NO CHEMICAL ADDITION

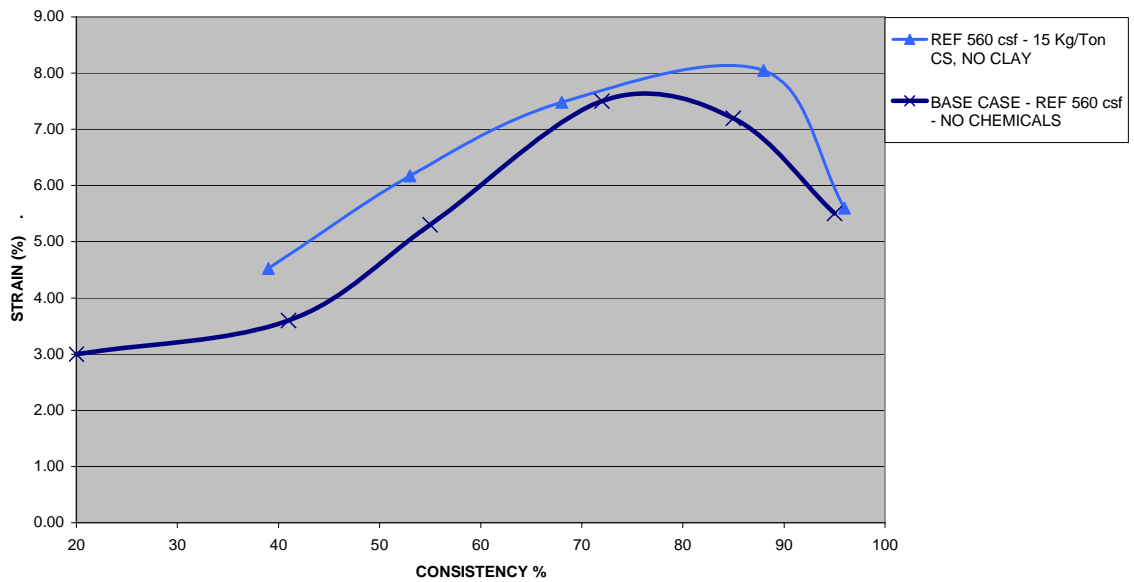




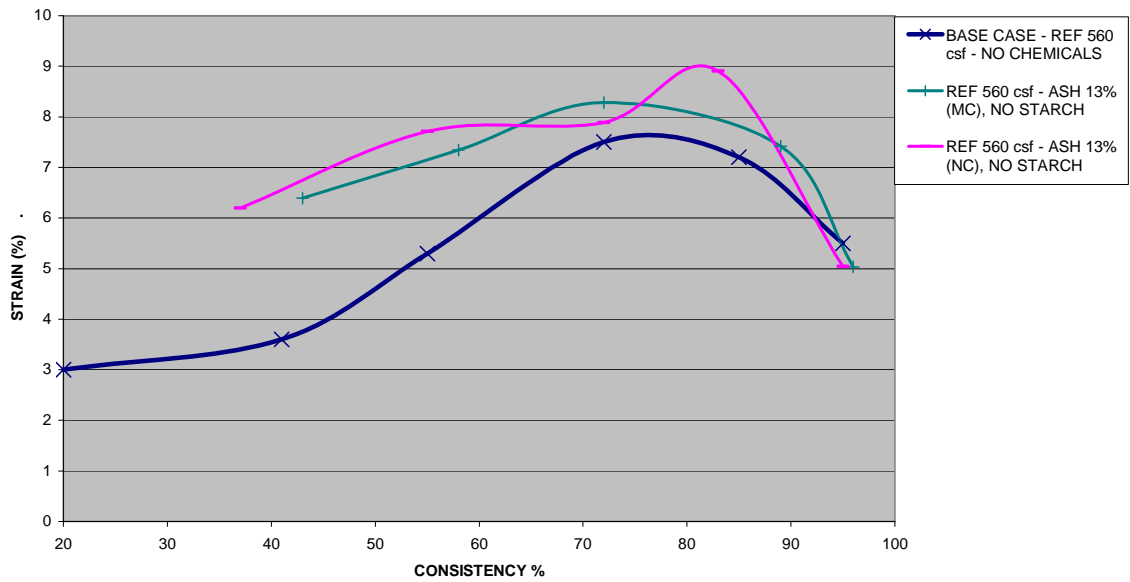
% STRAIN AT MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay); 318 g/m² (Modified Clay); 340 g/m² (Normal Clay & C-Starch)
ASH CONTENT 23%; REFINING 560 csf



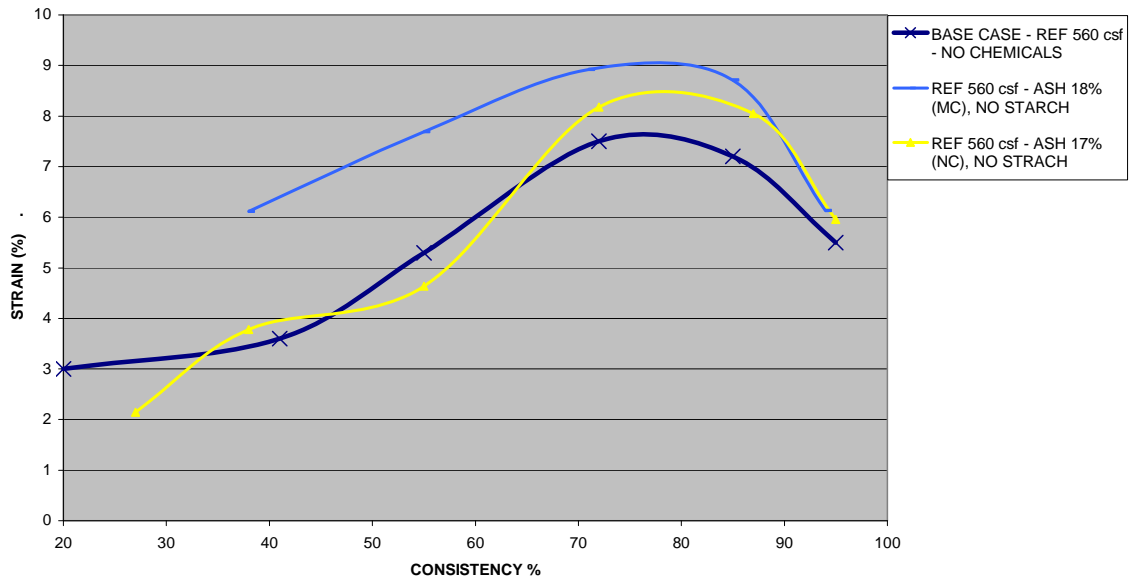
% STRAIN AT MAXIMU LOAD Vs CONSISTENCY
BASE CASE VS BASE CASE + 15 kg/Ton C-STARCH; NO CLAY
300 g/m²



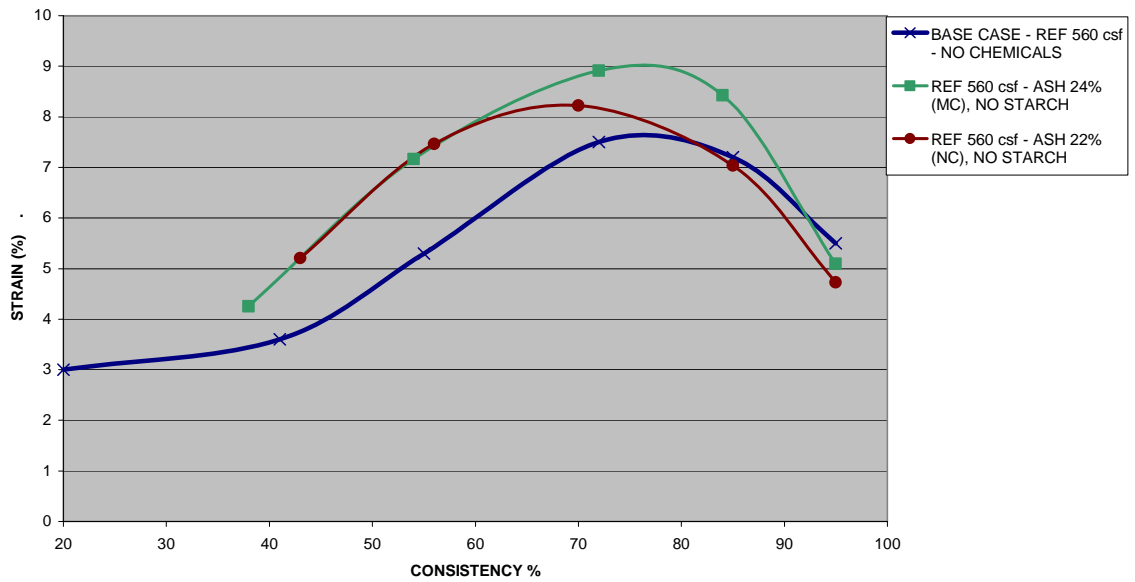
% STRAIN AT MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay) & 318 g/m² (Modified Clay)
ASH CONTENT 13%, NO STARCH; REFINING 560 csf



% STRAIN AT MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay) & 318 g/m² (Modified Clay)
ASH CONTENT 17%, NO STARCH; REFINING 560 csf

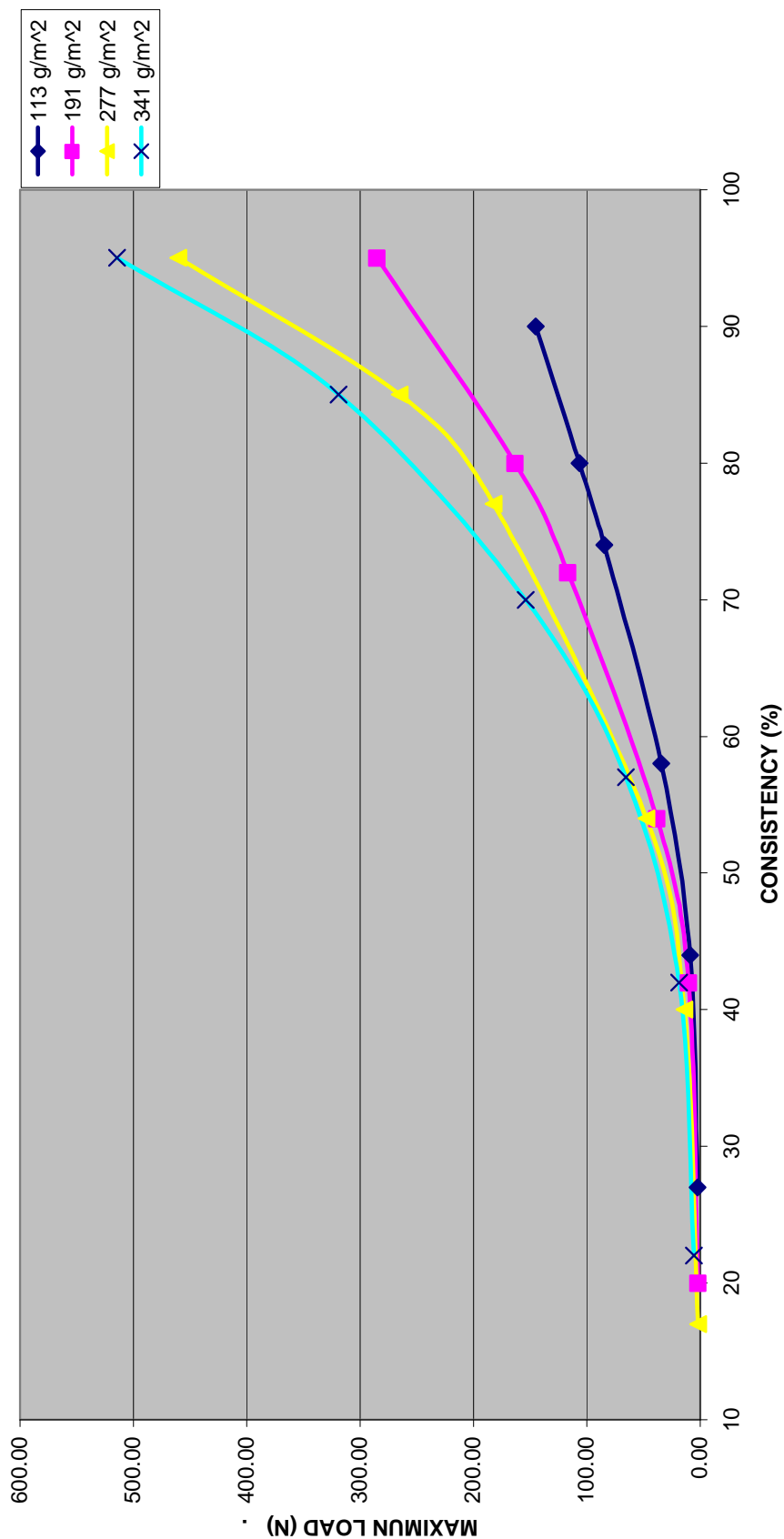


% STRAIN AT MAXIMUM LOAD Vs CONSISTENCY
310 g/m² (Normal Clay) & 318 g/m² (Modified Clay)
ASH CONTENT 23%, NO STARCH; REFINING 560 csf

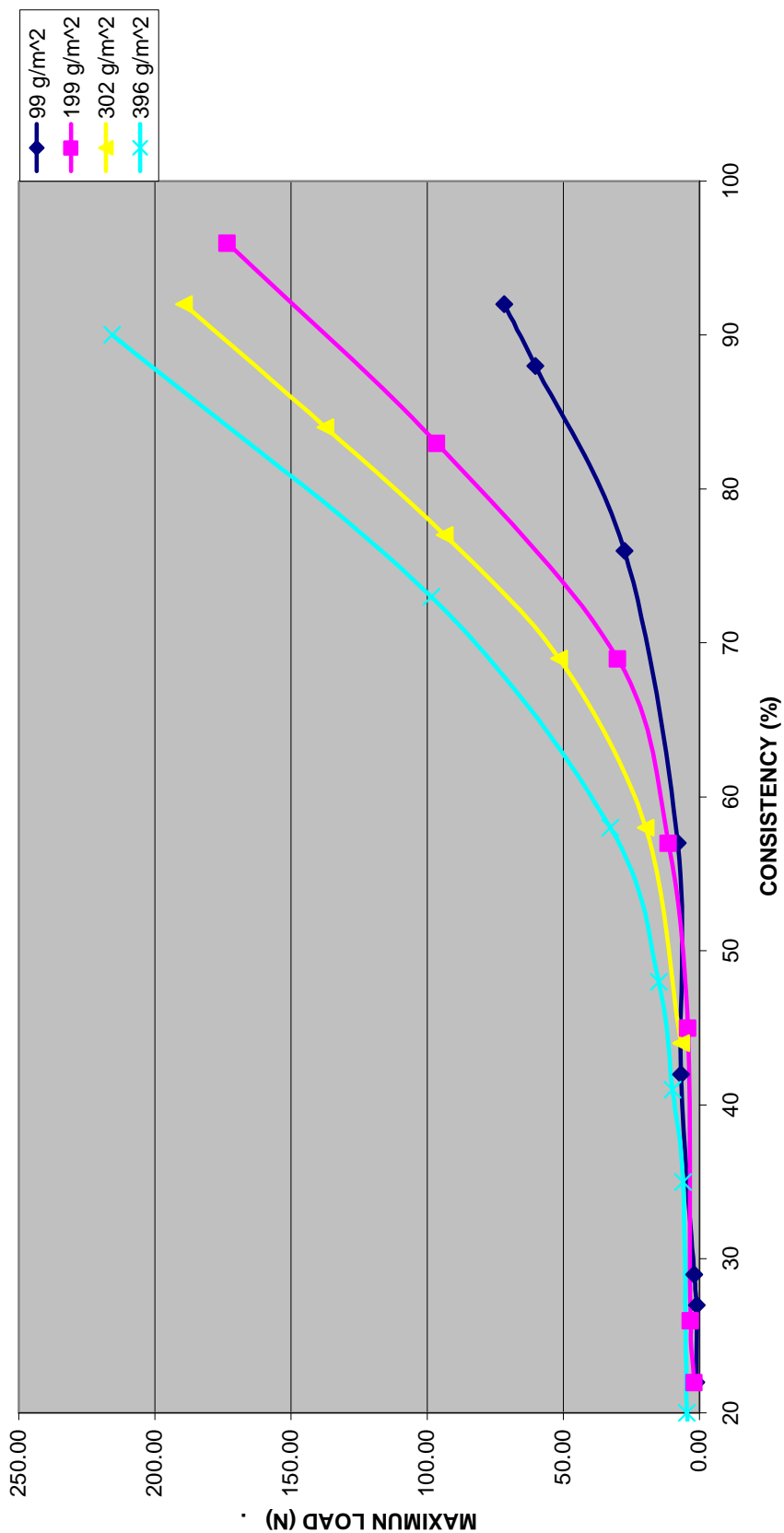


**APPENDIX E.4: TENSILE STRENGTH VS SOLIDS FOR DIFFERENT BASIS
WEIGHTS – CASES 1 TO 3**

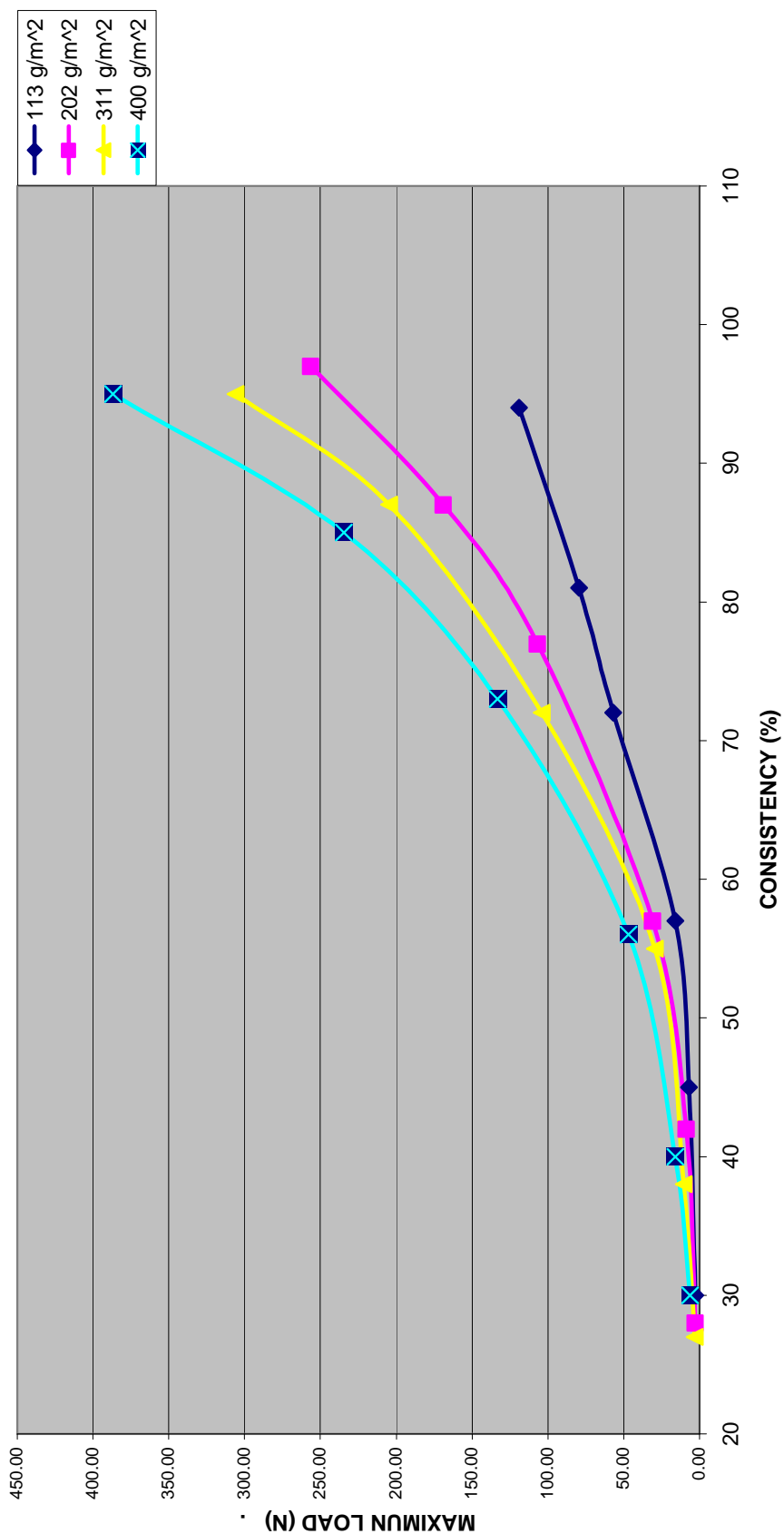
TENSILE LOAD Vs PAPER CONSISTENCY
CASE 1
REFINING 560 csf; NO CHEMICALS
BASIS WEIGHT (113 To 341 g/m²)



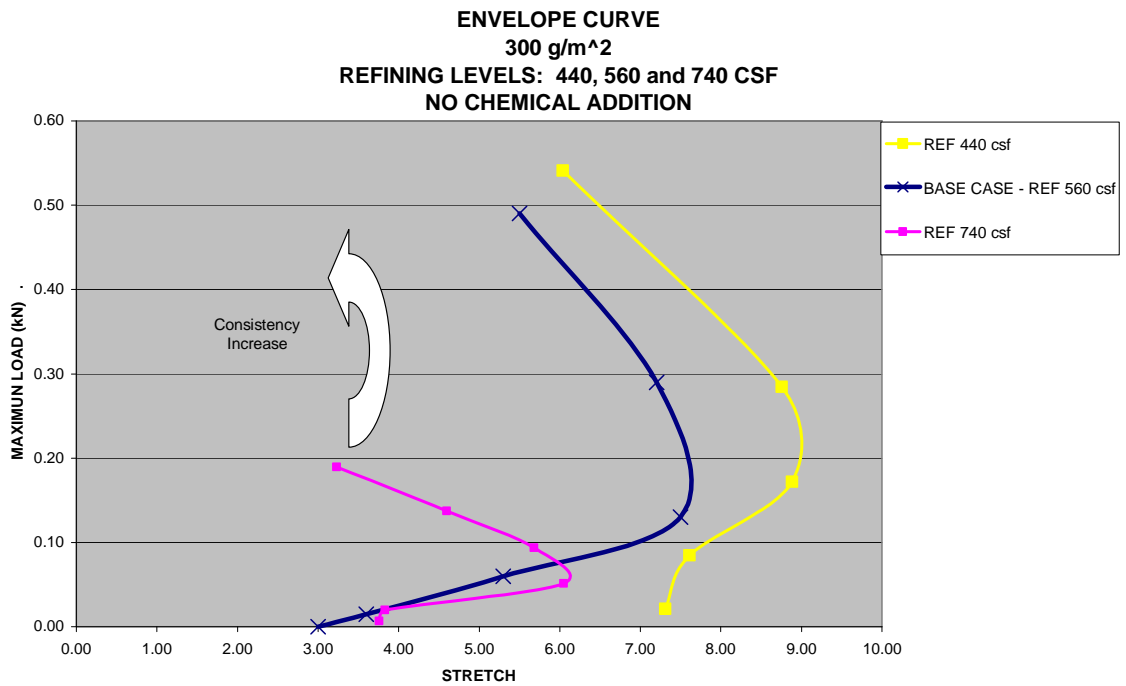
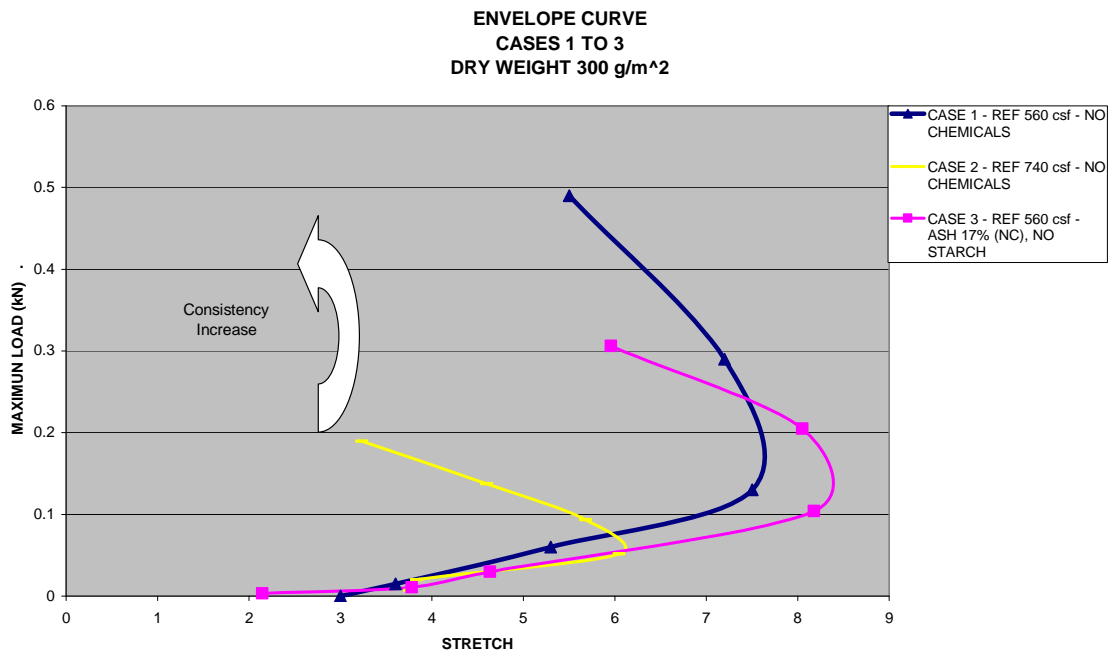
TENSILE LOAD Vs PAPER CONSISTENCY
CASE 2
REFINING 740 csf; NO CHEMICALS
BASIS WEIGHT (99 To 396 g/m²)

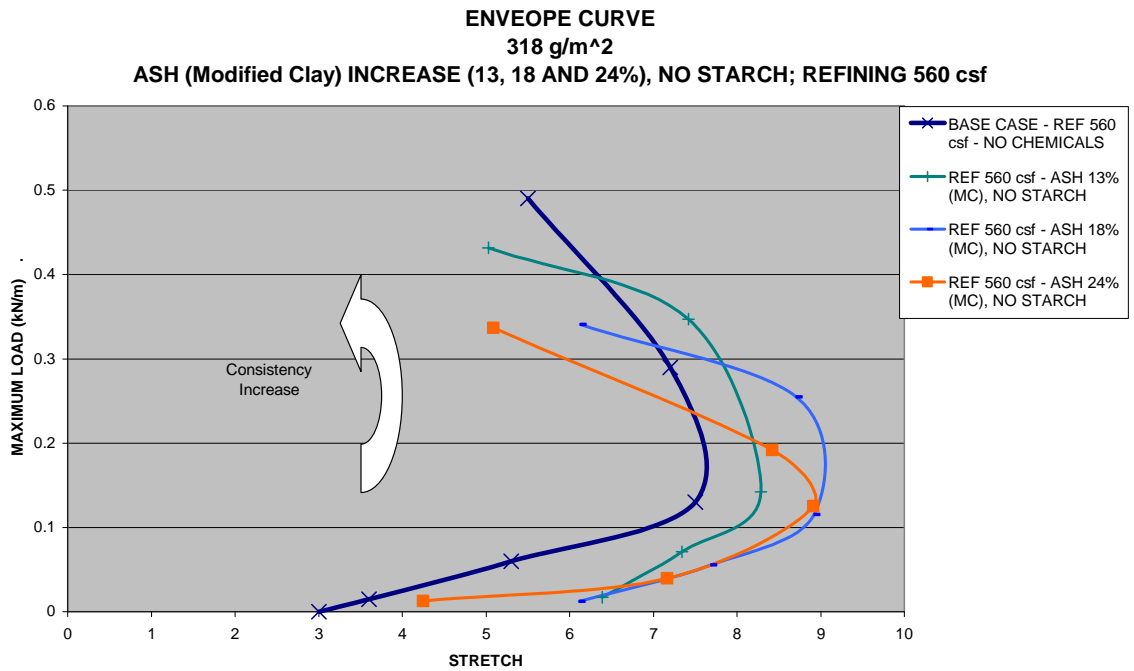
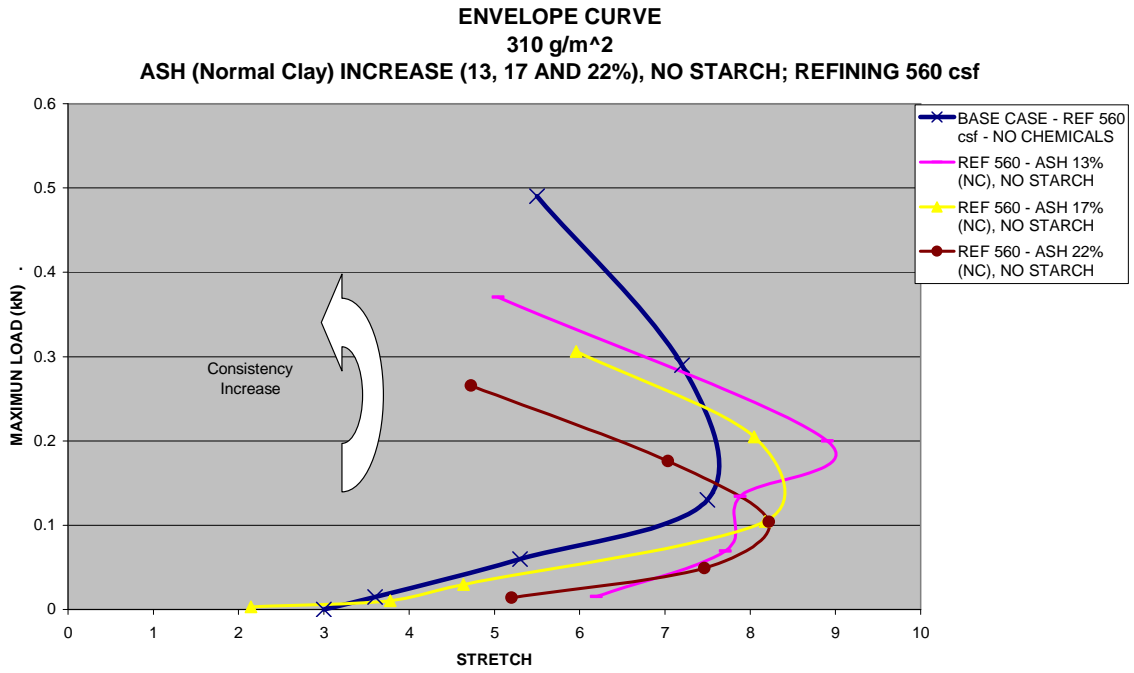


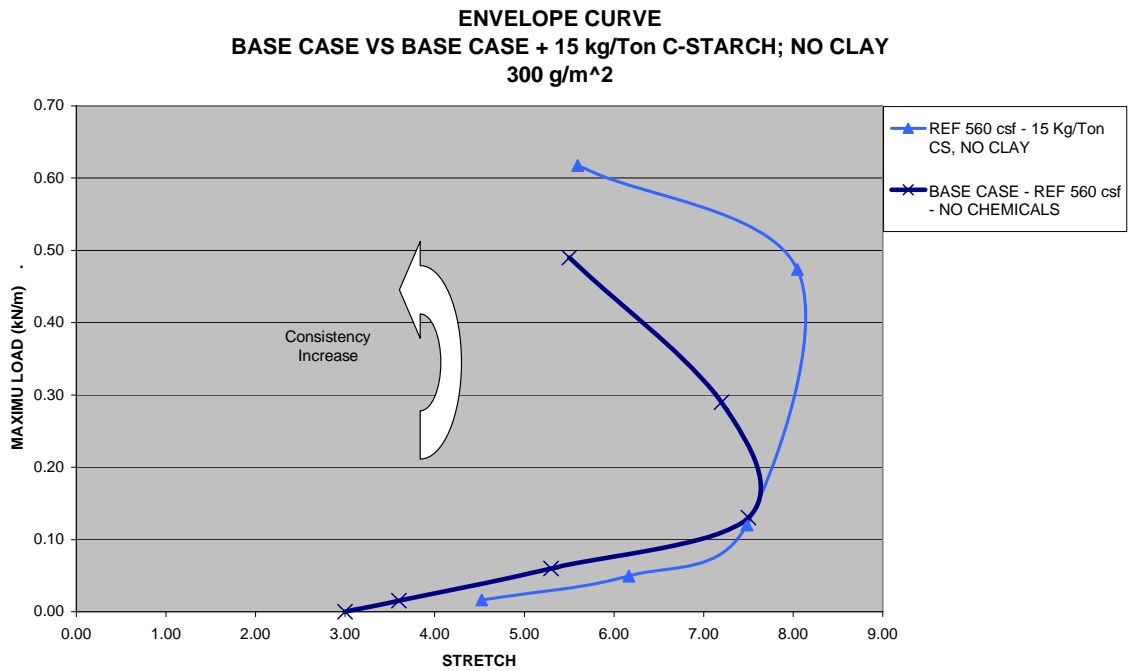
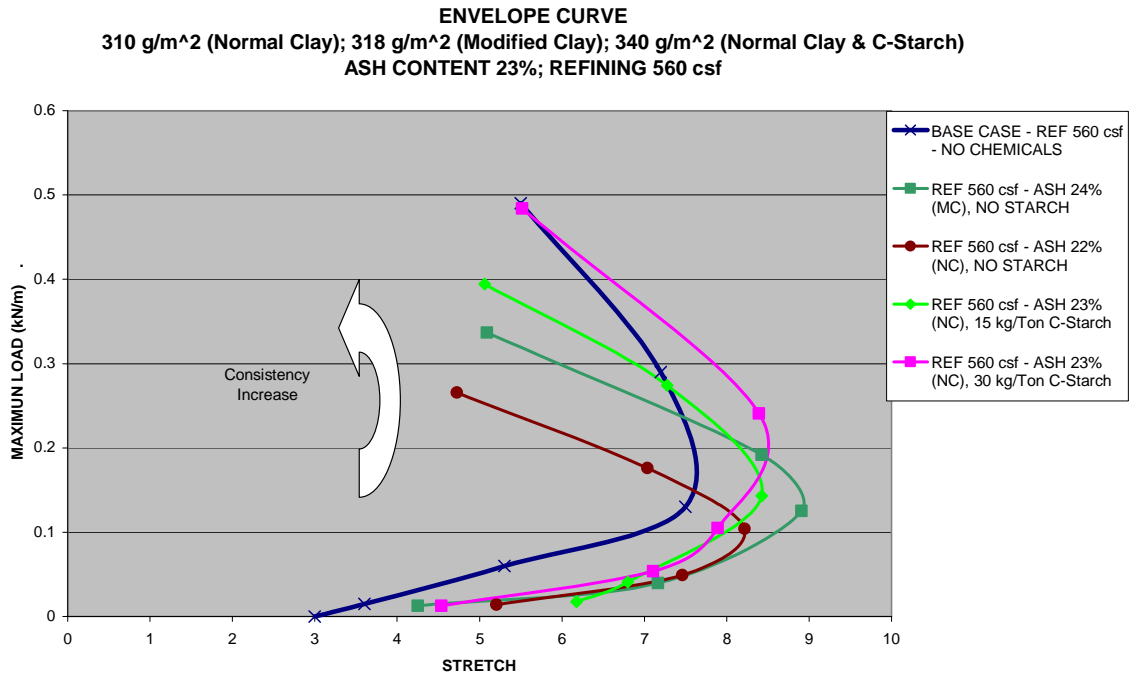
TENSILE LOAD Vs PAPER CONSISTENCY
CASE 3
REFINING 560 csf; ASH CONTENT = 17% (Normal clay) , NO STARCH
BASIS WEIGHT (101 To 400 g/m²)

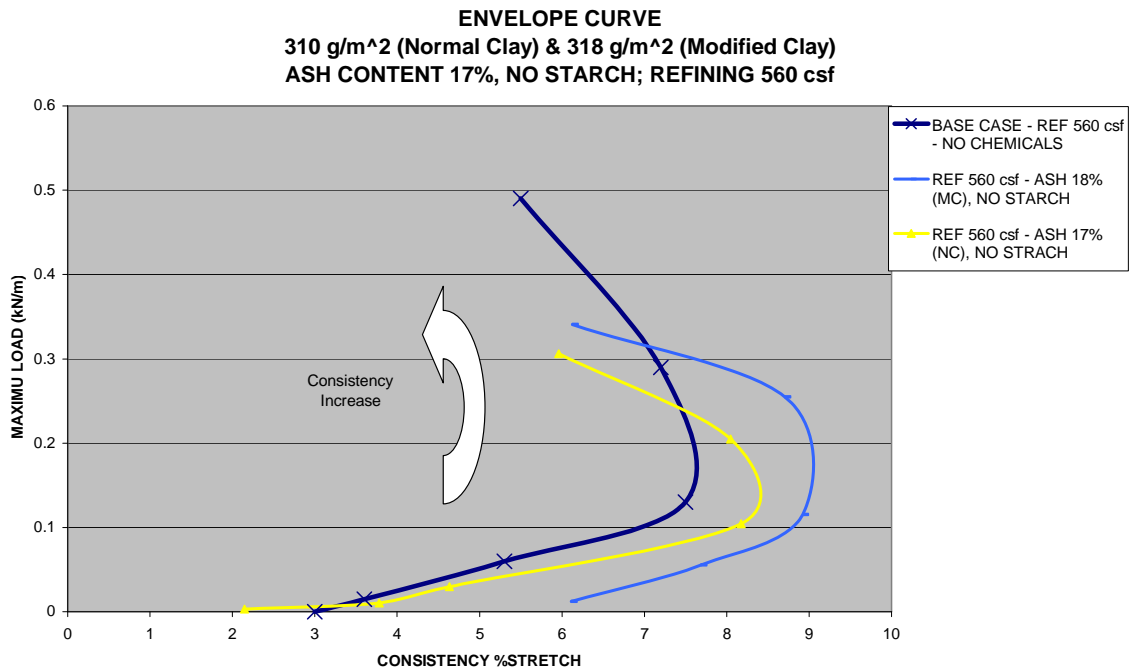
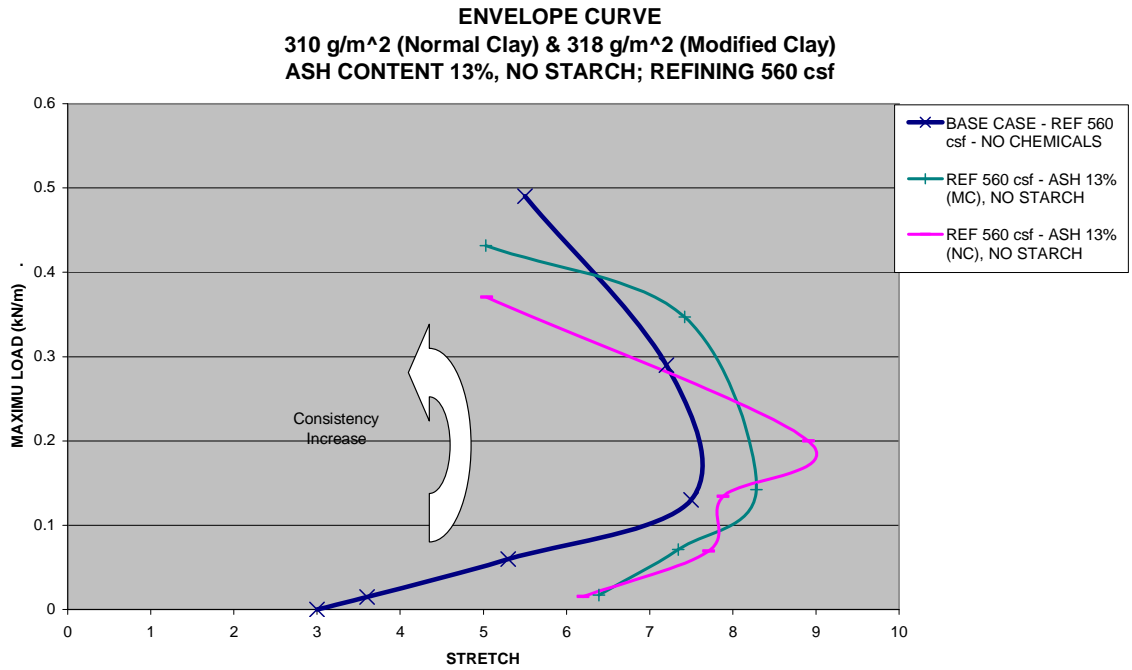


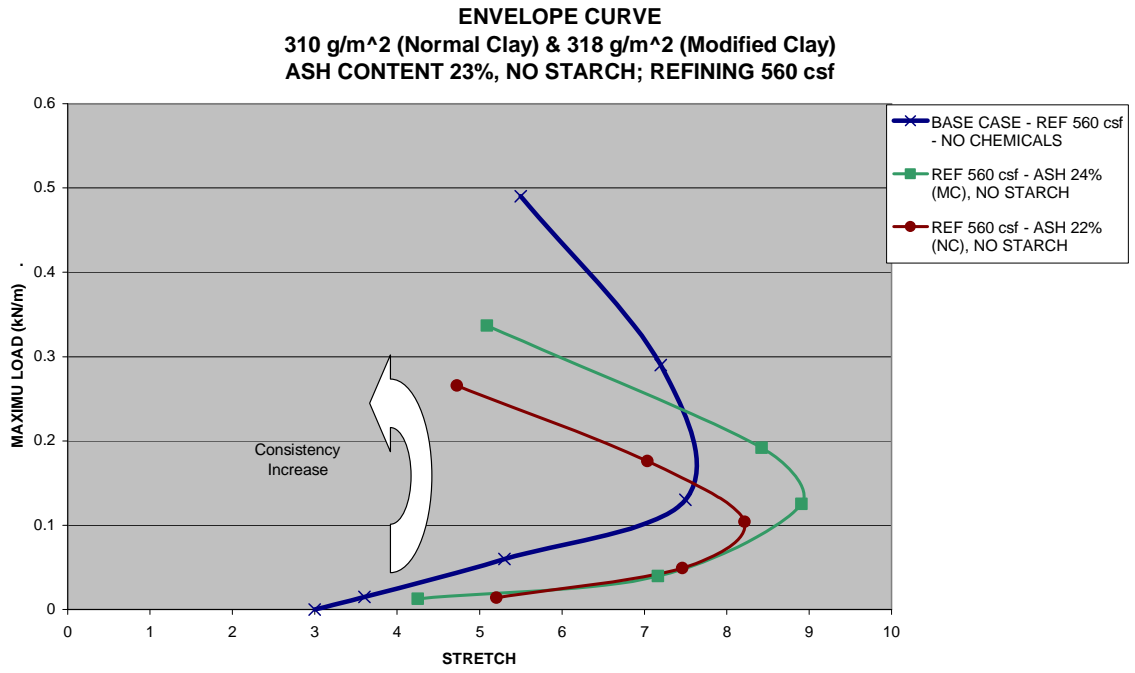
APPENDIX F: ENVELOPE CURVES











**APPENDIX G: TENSILE AND COHESIVE STRENGTH INDEX DATA
FOR ALL BASIS WEIGHTS – CASE 1 TO 3**

TENSILE STRENGTH INDEX [Nm/g] - CASE 1

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
101	1.95	7.02	15.59	27.29	40.93	48.73
191	1.65	5.15	12.37	22.26	34.01	42.05
277	1.71	4.55	9.95	19.61	29.28	37.66
341	1.73	4.50	9.24	17.90	29.44	36.95

COHESIVE STRENGTH INDEX [Nm/g] - CASE 1

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
101	0.06	0.13	0.30	0.53	0.80	1.04
191	0.03	0.07	0.16	0.28	0.42	0.55
277	0.02	0.05	0.11	0.19	0.29	0.38
341	0.02	0.04	0.09	0.16	0.24	0.31

TENSILE STRENGTH INDEX [Nm/g] - CASE 2

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
99	1.59	2.78	3.98	7.95	14.32	19.88
199	1.38	1.98	3.17	6.73	15.83	21.37
302	1.04	1.56	3.13	7.56	14.60	18.51
396	0.89	1.79	3.98	7.95	14.42	17.90

COHESIVE STRENGTH INDEX [Nm/g] - CASE 2

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
99	0.04	0.05	0.08	0.18	0.41	0.58
199	0.02	0.02	0.04	0.09	0.20	0.29
302	0.01	0.02	0.02	0.06	0.13	0.19
396	0.01	0.01	0.02	0.04	0.10	0.14

TENSILE STRENGTH INDEX [Nm/g] - CASE 3

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
113	1.74	3.48	7.32	17.42	26.13	31.36
202	1.75	2.92	7.02	15.20	23.39	30.21
311	1.39	2.66	6.08	11.90	19.24	24.05
400	1.48	2.95	6.10	11.32	18.11	23.13

COHESIVE STRENGTH INDEX [Nm/g] - CASE 3

BW (g/m ²)	SOLIDS CONTENT					
	40	50	60	70	80	85
113	0.04	0.09	0.17	0.32	0.52	0.59
202	0.02	0.05	0.10	0.18	0.29	0.33
311	0.01	0.03	0.06	0.12	0.19	0.22
400	0.01	0.02	0.05	0.09	0.15	0.17

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